DESIGN AND EVALUATION OF MEASUREMENT INSTRUMENTATION USED FOR HIGH ENERGY IMPACTS ON FRESH POST-MORTEM HUMAN SUBJECTS

A Thesis

Presented in Partial Fulfillment of the Requirements for

The Degree of Bachelors in Science with Distinction in the Undergraduate School

of The Ohio State University

By,

Kiel Pfefferle

****

The Ohio State University

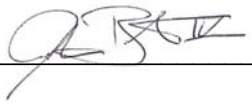
2006

Honors Examination Committee:

Dr. John Bolte, IV, Advisor

Dr. James Schmiedeler

Approved by



Advisor

Department of Mechanical Engineering

ABSTRACT

The femur injury criterion for anthropomorphic test devices (ATDs), used in car crash testing, is well established in crash biomechanics literature: however, the knee slider criterion and the tibial injury indices have less well-developed biomechanical bases. There is a need to investigate the biomechanical properties and behavior of the posterior cruciate ligament (PCL) and tibia during high energy impacts. The Ohio State University Injury Biomechanics Research Laboratory has been conducting high energy tibia impacts on fresh post-mortem human subjects (PMHS). This research project uses PMHS and focuses on the displacement of the tibia in relation to the femur while the tibia is loaded anteriorly as documented in frontal car crashes.

The objective of this research is to design and evaluate a measurement system used in high energy tibia impact testing on PMHS; this system should allow for accurate measurement of PCL and tibia displacements as well as identifying the time at which injury to the specimen occurred. Since February 2005, seven PMHS (13 tibias) have been tested. A number of constraints have been placed on the test setup in order to reduce the number of test variables. These constraints include eliminating an applied tibia load, reducing the femur angle and securing the foot to the test platform. The tibia displacement is currently measured using three tri-axial accelerometers, one attached anteriorly to the femur and two attached to the tibia, anteriorly and medially. A positive comparison has been made between the relative tibia displacements recorded from accelerometers and displacements recorded from high speed video. In all tests resulting in a tibia fracture the time of failure has been clearly identified, but determining the time of failure in a test which results in a ligament injury has proven to be more difficult. With the use of the accelerometers to determine tibia displacement and suturing the DVRT to the PCL, determining the time of failure for both tibia fractures and PCL injuries has been achieved.

Now that the time of injury for tibia and PCL failures can be determined and the relative tibia displacement can be accurately measured, the next step in this research is to start removing the constraints initially placed on the test setup. Removing the constraints placed on the test setup will provide a more “real world” situation allowing future researchers to obtain the biomechanical properties of the knee in a frontal car crash. Finally, the test data can be used to develop knee slider criterion and tibia displacement injury index.

Dedicated to my friends and family who were always there to support me. Without them I could have never completed this research.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisor Dr. John H. Bolte, IV, without him I would have never been introduced to the exciting field of injury biomechanics. Dr. Bolte was always willing to meet with me to discuss any questions I had about my current research or classes. Dr. Bolte always went above and beyond his role as an honors advisor, by being my mentor and friend.

Next I would like to thank Rod Herriot and Joe McFadden for all of their hard work during test day. With Rod and Joe test days would have turned into test weeks. I have learned a great deal from Rod and Joe. They helped me analyze data and come up with creative solutions for problems in the lab.

I would like to acknowledge Mark Whitmer for always preparing the PMHS and contacting us as soon as a subject came in. I would also like to thank John Landoll for conducting the BMD scans for us at a moments notice.

I would like to thank Patrick Biondillo and Jim Stricklin for their technical support during test day. Pat and Jim always ensured the data acquisition system was operating properly.

I would like to thank Josh Shaw for taking the time to teach me about matrix transformations and also for allowing me to adapt his MATLAB code for this project.

Finally, I would like to thank Jessica Sparks, Alexia Fountain and Angela Xavier for their assistance on test day. The girls helped me numerous times when I was having trouble processing data or just having a rough day.

VITA

September 9, 1982……Born- Tiffin, Ohio

FIELDS OF STUDY

Major Field: Mechanical Engineering

Minor Field: Biomedical Engineering

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Currently, knee injuries account for 10% of all frontal car crash injuries [1]. Although knee injuries account for a small percent of frontal car crash injuries they are attributed to an estimated annual 225-720 million dollars in cost [2, 3]. The femur injury criterion for anthropomorphic test devices (ATDs), used in car crash testing, is well established in crash biomechanics literature: however, research efforts to establish the knee slider criterion and the tibial injury indices have been limited in scope and effort. There is a need to investigate the biomechanical properties and behavior of the knee, including posterior cruciate ligament (PCL) and tibia, during high energy impacts.

Knee injuries in frontal car crashes are predominately caused when the lower extremity of a frontal passenger comes in contact with the knee bolster or steering column. When the knee bolster contacts the lower extremity below the knee, a compressive load is placed on the tibia causing the tibia to sublux posteriorly in relation to the femur. This posterior displacement may result in a PCL injury.

CHAPTER 2

ANATOMY

Section 2.1: Bones of the Leg

The femur as shown in Figure 1 is the only bone of the thigh. The femur is the longest and heaviest bone in the human body. The head of the femur articulates in a circular depression of the pelvis known as the acetabulum. The shaft of the femur has a slight curve to allow the knee joint to be in line with the body's center of gravity. The distal end (near knee joint) of the knee joint is characterized by two rounded structures known as the medial and lateral condyles as shown in Figure 2. These femoral condyles are the articulating surfaces of the femur in the knee joint.

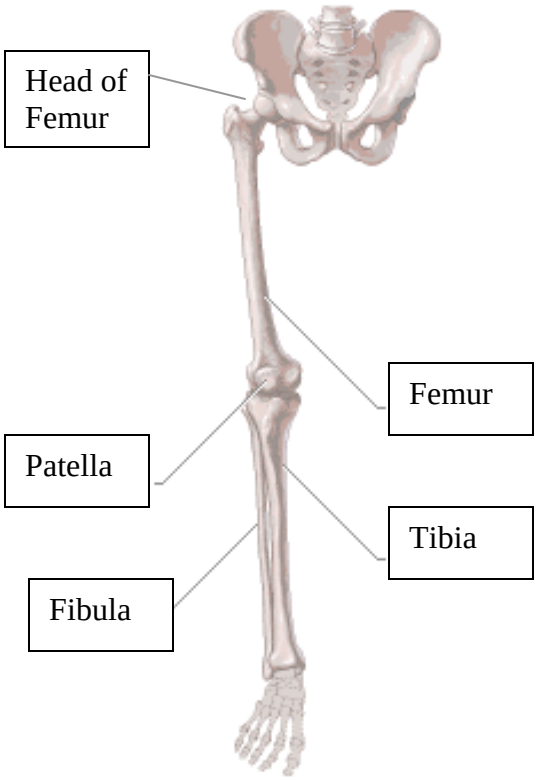


Figure 1: Bones of the Leg (from: www.encarta.msn.com)

The patella commonly known as the knee cap is located on the anterior (front) surface of the knee joint as shown in Figure 1. The patella serves to protect the knee joint and increase the leverage of the quadriceps femoris muscle (described in section 2.2) as it extends the leg at the knee.

The tibia is the main weight bearing bone of the lower leg. The proximal end (head) of the tibia is characterized by two slightly concave surfaces known as the medial and lateral condyles as shown in Figure 2. These tibial condyles are the articulating surfaces of the tibia in the knee. The proximal (near knee joint) end of the tibia is often refered to as the tibia plateau. The tibia tuberosity is located on the anterior part of the

tibia , just below the plateau, and is the attachment site of the patellar tendon (described in section 2.3).

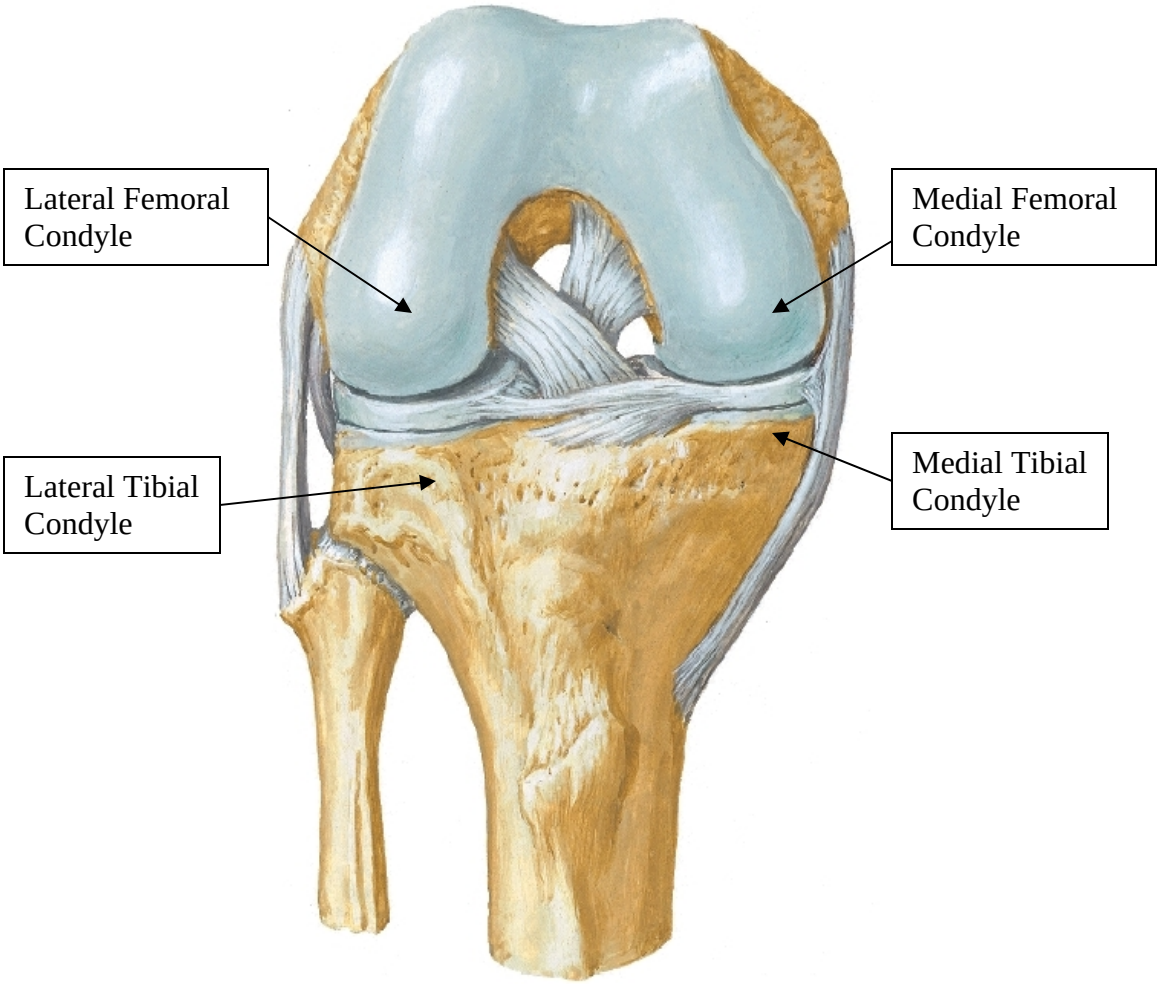


Figure 2: Articulating Structures of the knee [11]

The fibula is a long slender bone that runs parallel to the tibia as shown in Figure 1. The fibula is more important for muscle attachment than for weight bearing support.

Section 2.2 Muscles Controlling the Knee

The muscle group responsible for extending the leg at the knee is known as quadriceps femoris. Quadriceps femoris is made up of four muscles; rectus femoris, vastus lateralis, vastus medialis and vastus intermedius. Rectus femoris is the most superficial (close to skin) of the four muscles. Vastus lateralis is positioned laterally on the leg. Vastus medialis occupies the medial position along the thigh. Vastus intermedius lie deep to the rectus femoris. The four muscles of quadricps femoris are shown in Figure 3.

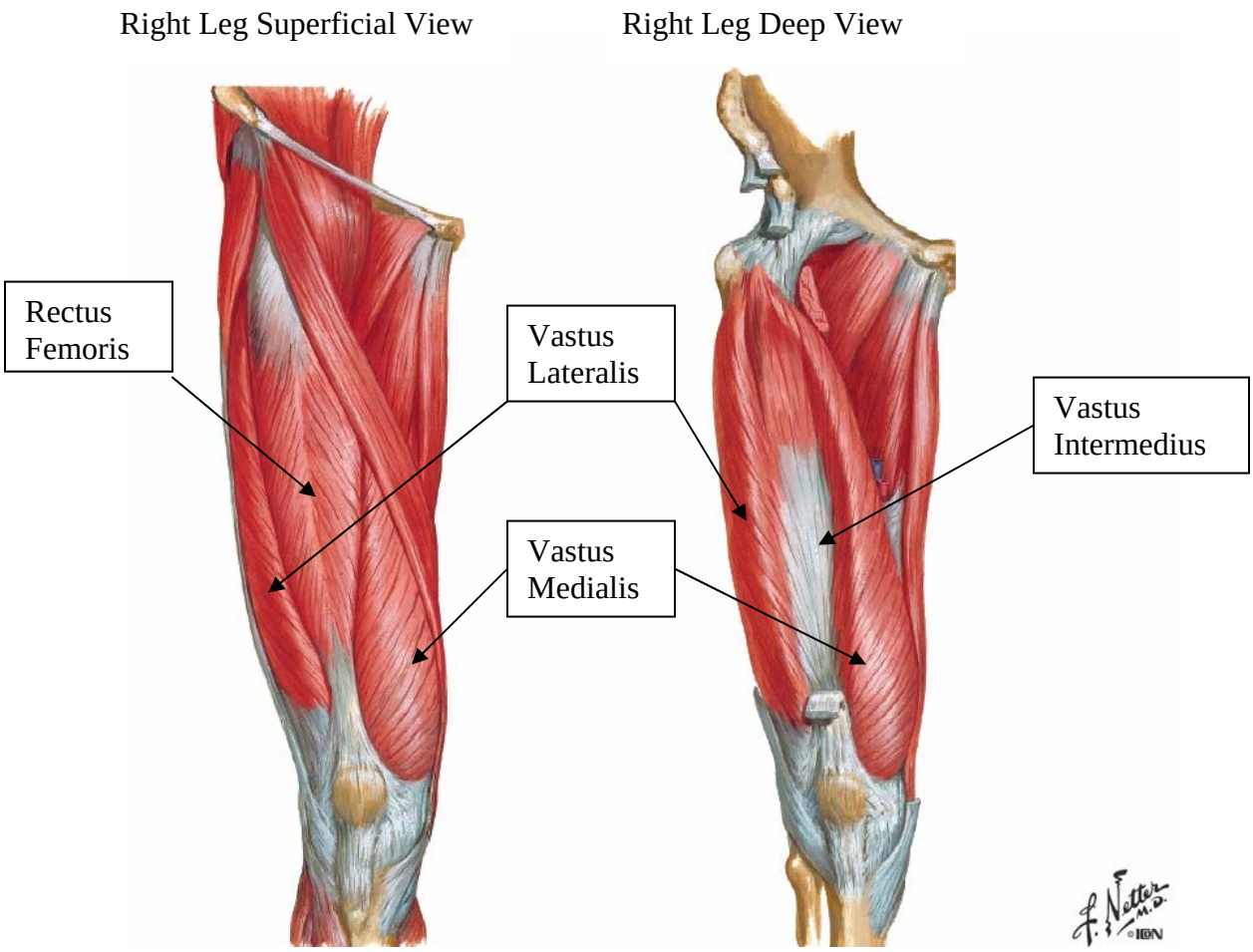


Figure 3: Four Muscles of the Quadriceps Femoris Muscle [11]

There are three muscles that are responsible for flexing the leg at the knee. These muscles are commonly know as the hamstring, and are located on the posterior (rear) of the thigh. Biceps femoris is located on the laterial portion of the thigh. Semitendinosus is located on the posterior medial portion of the thigh and semimembranosus is located deep to semitendinosus. The locations of the three hamstring muscles are shown in Figure 4.

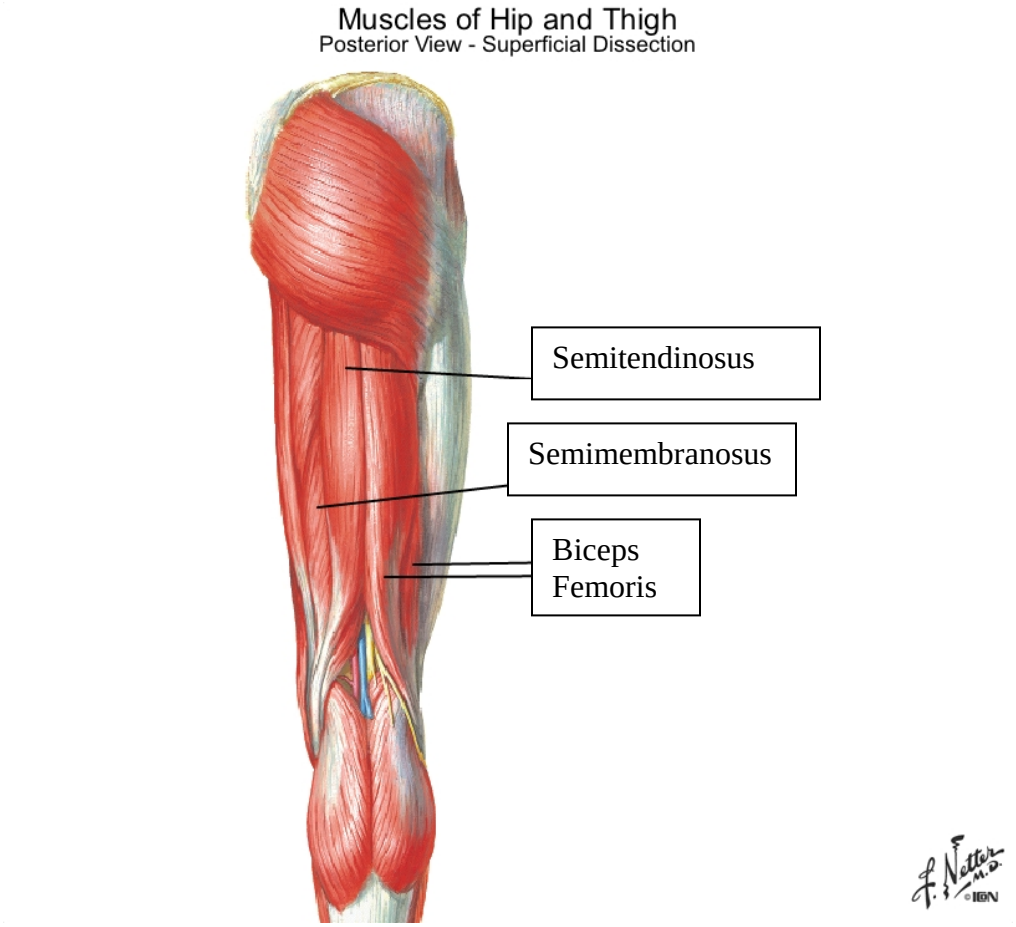


Figure 4: Location of the Three Hamstring Muscles [11]

Section 2.3 Major Tendons and Ligaments of the knee

The tendon that connects the patella to the tibial tuberocity is known as the patellar tendon. The ligaments that are responsible for stability in the anterior/posterior direction are known as the posterior cruciate ligament (PCL) and the anterior cruciate ligament (ACL). The PCL lies deep within the knee joint and runs from the anterior femur to the posterior tibia. The ACL, which lies anterior to the PCL, runs from the posterior femur to the anterior tibia. The locations of the ACL and PCL are shown in Figure 5.

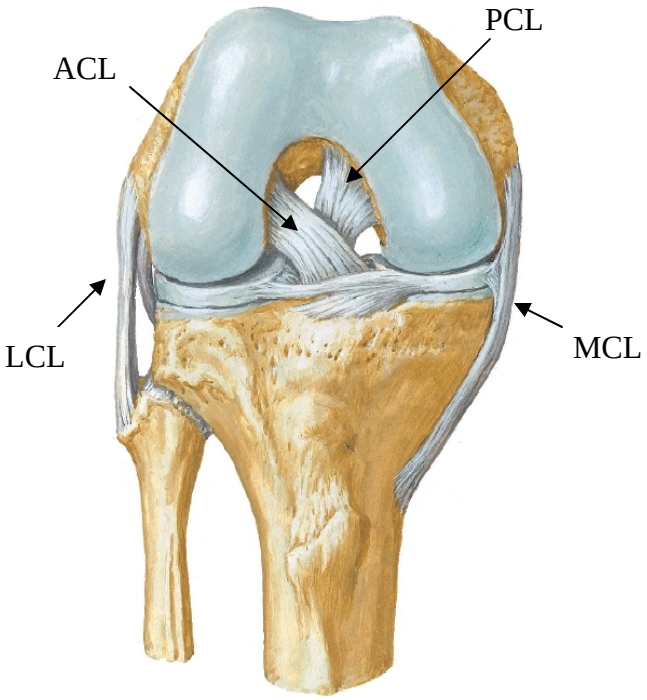


Figure 5: Major Ligaments of the Knee [11]

Ligaments only provide resistance when placed in tension. As shown in Figure 6, the PCL provides resistance to posterior tibia displacement relative to the femur. The

ACL provides resistance to anterior tibia displacement relative to the femur. As the knee becomes flex, the tension on the PCL increases while the ACL tension decreases. The increased tension on the PCL in the flexed position makes the PCL vulnerable to injury from posterior displacement.

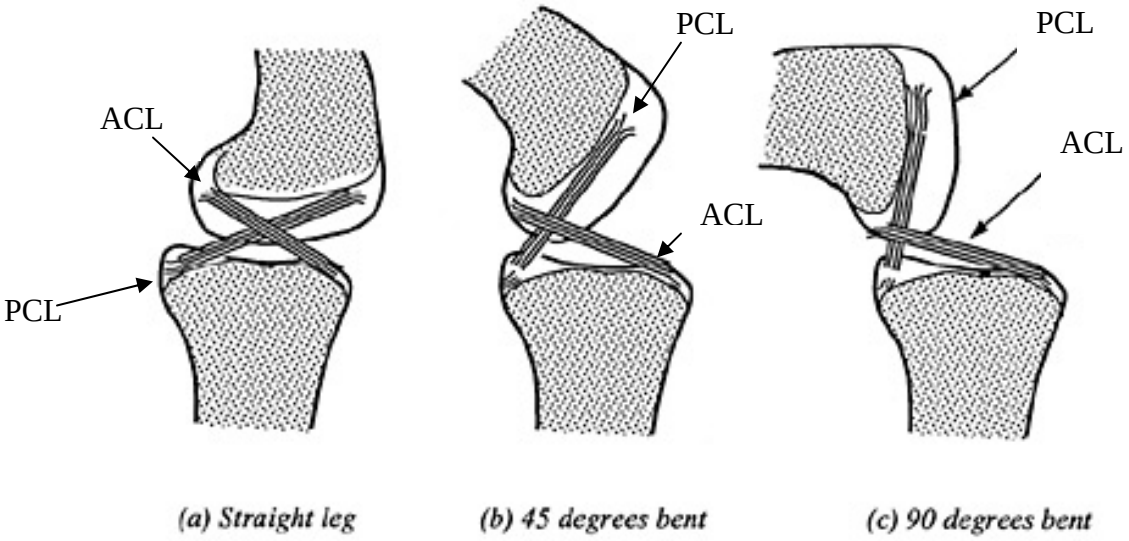


Figure 6: ACL and PCL Stability Properties (www.answersingensis.org)

The ligaments that are responsible for the medial/lateral stability of the knee are known as the lateral collateral ligament (LCL) and the medial collateral ligament (MCL). The LCL is located on the lateral portion of the knee, connecting the femur to the fibula. The MCL is located on the medial portion of the knee, connecting the femur to the tibia. The locations of the LCL and MCL are shown in Figure 5.

CHAPTER 3

PREVIOUS RESEARCH

Viano et al [4] conducted research, in which ten cadavers (twenty legs) were tested to investigate knee and tibia impact biomechanics and kinematics. Viano used three different dynamic test configurations; knee impacts with a 110^{o} flexion angle, lower leg impacts with a 90^{o} flexion angle and knee-tibia impacts with a 90^{o} flexion angle. Following dynamic testing, Viano also potted the tibia and femur of five of these legs for further testing. Viano quasistatically displaced the tibia, while keeping the femur flexed at 90^{o}, until failure occurred to determine the stiffness of the knee and displacement tolerance of the tibia. Viano documented that the PCL failed at 14.4mm of tibia displacement.

The current injury criterion (15mm of tibia displacement) is based on theses values obtained by Viano. The tibia injury criterion and knee slider stiffness for anthropomorphic test devices (ATDs), used in car crash testing, are not based on dynamic biomechanical test data.

Balasubramanian et al [5] attempted to dynamically verify the PCL injury criterion. Balasubramanian dynamically tested fourteen legs in three different test setups. The tests conducted by Balasubramanian produced a number of various injuries. Of these injuries, a total of six PCL related injuries were recorded with an average tibia displacement of 17.2±2.8mm at time of injury. Although the dynamic test data obtained

by Balasubramanian was close to the values obtianed by Viano, the test setup that was used was not supported by any real world conditions. Balasubramanian stated:

> *"However, the current setup may be an over constrained case compared to typical impact conditions and it is not clear if could be used to estimate the risk of injury to particular anatomical structures."*

Bartsch et al [6] conducted cadaver research in which the proximal tibia was dynamically impacted. Bartsch developed a test setup that would accurately replicate real world test conditions. Bartsch analyzed the lower extremity loading conditions of a Hybrid III 50^{th} percentile ATD in a series of twenty-eight frontal barrier to vehicle or vehicle to vehicle crash tests from late model vehicles. Bartsch isolated the lower extremity from the Hybrid III ATD and developed a test setup that produced results that were similar to the vehicle crash data. Bartsch then conducted dynamic impacts on eight isolated post-mortem human subject (PMHS) legs. Although the test setup developed by Bartsch has been verified to produce a real world test condition, the accuracy of the measurement instrumentation used in the PMHS test was less certain.

CHAPTER 4

OBJECTIVE

Due to the visco-elastic properties of biological materials, the current knee injury criterion needs to be verified by dynamic impacts using a “real world” test setup. Therefore, there is a need to develop measurement instrumentation that will allow accurate measurements during dynamic tibia impacts on PMHS without affecting the biomechanical response of the subject. The objective of this research is to develop measurement instrumentation that will complete the following tasks:

- Accurately measure tibia displacement relative to the femur
- Accurately measure PCL displacement
- Identify the time of injury for both ligament and bone failures

CHAPTER 5

METHODS

Section 5.1 Introduction to Methods

Since February 2005, seven fresh PMHS (thirteen legs) have been dynamically tested at The Ohio State University Injury Biomechanics Research Laboratory. The testing was completed to investigate the biomechanical response and properties of the lower extremity in frontal tibia impacts. Before accepting the PMHS, a Dual Energy X-ray Absortiometry (DEXA) scan was performed to ensure that the test subject did not suffer from osteoporosis, the subject's blood was tested for HIV/AIDS, Hepatitis B and Hepatitis C. A selection algorithm was used to determine whether the PMHS was suitable for this research project. The selection algorithm contains parameters such as minimum and maximum height and weight allowed. Subjects had to have at least seven inches of femur to allow for potting. No subjects with pre-existing knee injuries were accepted for this study. Please refer to Appendix A for the PMHS selection algorithm. To ensure the tests were conducted in a repeatable and efficient manor a test day protocol was created. Refer to appendix B to view a sample test protocol. The PMHS are divided into two test configuration groups. The division of the groups will be discussed in greater detail throughout sections 5.2 and 5.3.

A standard nomenclature for the test subjects has been developed to aid in the recognition of each impact. The nomenclature used for this project is the following; ####HTI##X## where the first two numbers are the last two digits of the year in which the test was completed. The next two numbers is the cadaver number. HTI is the project name; in this case it is High Tibia Impact. The next two numbers are the

impact speed in m/s (without a decimal point). The next letter denotes either the left or right leg. Finally, the last two numbers represent the impact number for that cadaver leg. For example, a test named 0601HTI14L02 means that the year in which the test was conducted was 2006. The cadaver was the first cadaver of the year to be tested for the high tibia impact project. The impact speed was 1.4m/s. The impact was the second impact conducted on the left leg.

The coordinate system used in all tests is defined in SAE J211 [9] and is the coordinate system used for test dummies. Each part of the subject has its own coordinate system that will translate or rotate with the part to which the coordinate system is designated. It is particularly important to understand this coordinate system when the leg is in the flexed position because the femur axis are in a different direction compared to the un-flexed leg as shown in Figure 7.

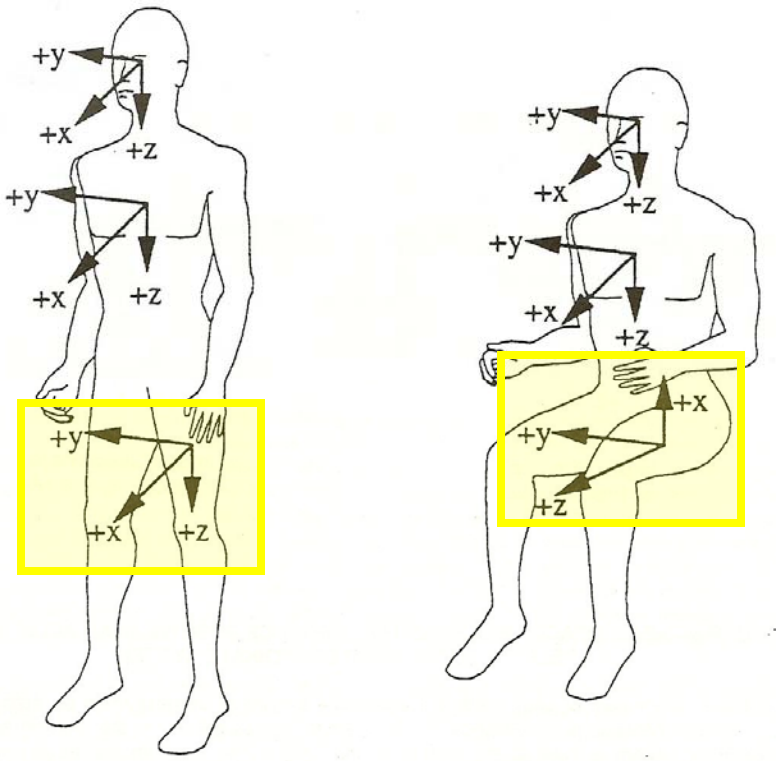


Figure 7: SAE J211 Coordinate System [9]

Section 5.2 Test Group 1

Test Group 1 consists of two PMHS (four legs) that were tested from February 2005 thru July 2005 including test 0501HTI and 0502HTI. The legs of each PMHS were removed at approximately mid-femur leaving seven inches of femur attached to the knee. The femurs were then securely potted using Bondo Ultimate Filler™ [Bondo Corporation, Atlanta, GA] to the test platform, shown in Figure 8. A six axis load cell (Model #2667 RA Denton Inc., Rochester, MI) was located behind the femur to measure the forces and moments acting on the femur. The displacement of the tibia was measured using a linear potentiometer (Model #180-3861, First Technology Safety Systems, Plymouth, MI) connected to a pin that ran in the anterior/posterior direction through the tibia. Forces transmitted through the foot were measured in the z and x axis using load cells (Models 1210AF-5K and 1210AF-2K respectively, Interface, Scottsdale, AZ) as shown in Figure 8. A constant force of 111 N was applied to the quadriceps muscle by clamping the muscle to a tensioned cable.

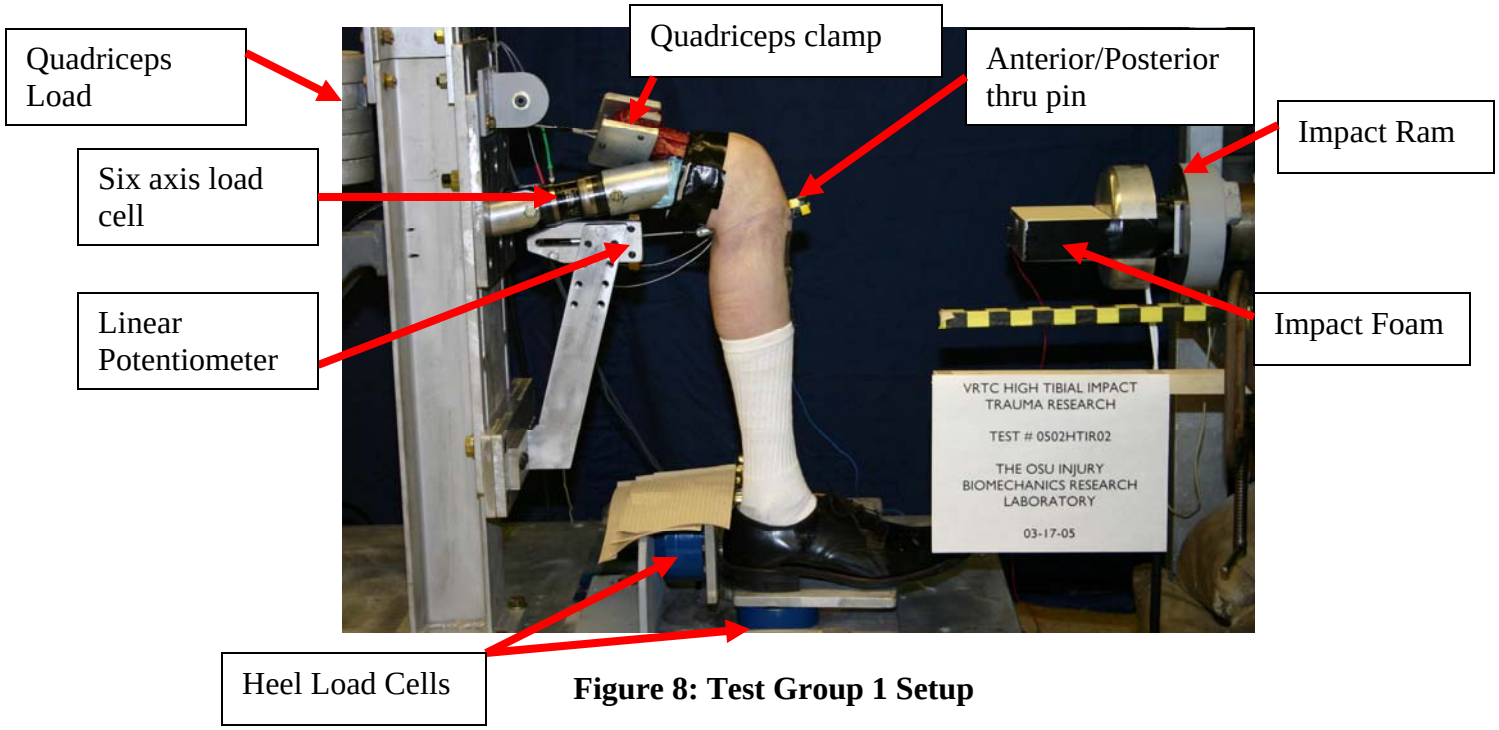


Figure 8: Test Group 1 Setup

Foam padding with a stiffness of 85 N/mm (Last-A-Foam, General Plastics Manufacturing Company, Tacoma, Washington) was placed on a 25.4kg pneumatic ram. The knee flexion angle for all tests in Group 1 was 100^{o}, which is measured by number of degrees the knee flexed from the straight position. When the knee is straight the flexion angle is zero degrees. Two micro-differential variable reluctance transducers (DVRT) [DEMOD-DVRT, MicroStrain Inc., Burlington, VT] were attached to the medial and lateral bands of the PCL to record PCL displacement. The ACL of each knee was removed to allow room to instrument the PCL. It has been shown that the ACL does not contribute to the stability of the flexed knee in posterior tibia displacement [7]. A DVRT is shown in Figure 9 and the implanted DVRTs are shown in Figure 10.

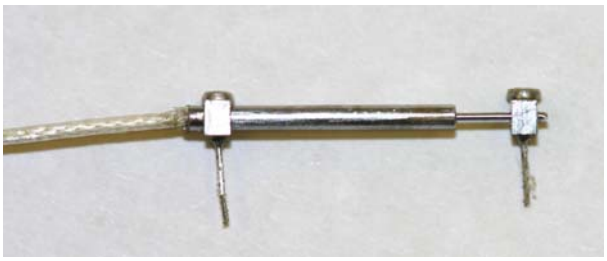


Figure 9: DVRT

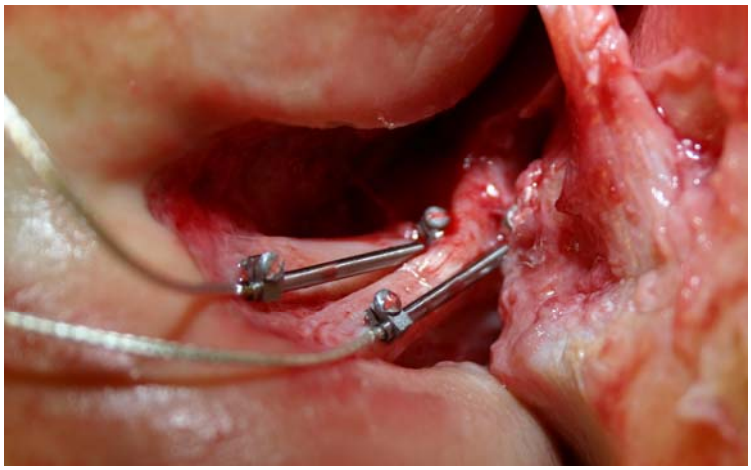


Figure 10: Implanted DVRTs

It was thought that the DVRTs may provide more accurate measurements if the patella was removed. For each of the three PMHS one of the legs was dissected, removing the patella and quadriceps muscle, while the contralateral knee was left intact. In test 0501HTI33L the knee was impacted one time, while in test 0501HTIR the leg was impacted at speeds of 2.7m/s, 3.2m/s, 3.6m/s and 4.3m/s. For test 0502HTI each leg was impacted at 2.9m/s and then 4.7m/s. The impact speed of 2.9m/s was believed to be lower than the injury threshold while 4.7m/s was believed to be above the required speed to produce injury. All tests were recorded using high speed video that was recorded at 1000 frames per second. The test matrix for Test Group 1 is shown in Table 1.

Table 1: Group 1 Test Matrix

Test Subject	Impact Speeds (m/s)	Knee Status	Tibia Displacement Instrumentation Technique	Quad Load (N)	DVRT Attachment	Foot Strapped Down	Knee Flexion Angle
0501HTIL	3.33	Dissected	Linear Pot.	N/A	Non-sutured	No	100º
0501HTIR	2.7, 3.2, 3.6, 4.3	Intact	Linear Pot.	111	Non-sutured	No	100º
0502HTIL	2.9, 4.7	Dissected	Linear Pot.	N/A	Non-sutured	No	100º
0502HTIR	2.9, 4.7	Intact	Linear Pot.	111	Non-sutured	No	100º

Section 5.3 Test Group 2

Test Group 2 consists of five PMHS (nine legs) that were tested from July 2005 thru April 2006; tests 0503HTI, 0504HTI, 0505HTI, 0601HTI and 0602HTI. The left leg of PMHS 0505HTI could not be used due to a pre-existing knee injury. The leg of each PMHS was removed at approximately the mid-femur leaving seven inches of femur attached to the knee. The femur load cell, heel load cells, ram padding, ram face and femur potting technique remained the same between Groups 1 and 2. The foot of all Test Group 2 subjects in was strapped to the test platform to reduce vertical motion during testing. The anterior/posterior pin that went thru the tibia and was connected to the linear

potentiometer was found to cause a stress riser in the tibia, producing pre-mature tibia fractures. It was also discovered that the linear potentiometer was bending during testing, providing inaccurate tibia displacement measurements. Therefore, the linear potentiometer was replaced with three tri-axial accelerometers. One tri-axial accelerometer was placed on the anterior femur while the other two where placed on the anterior and medial aspects of the tibia. The locations of the three tri-axial accelerometers are shown in Figure 11.

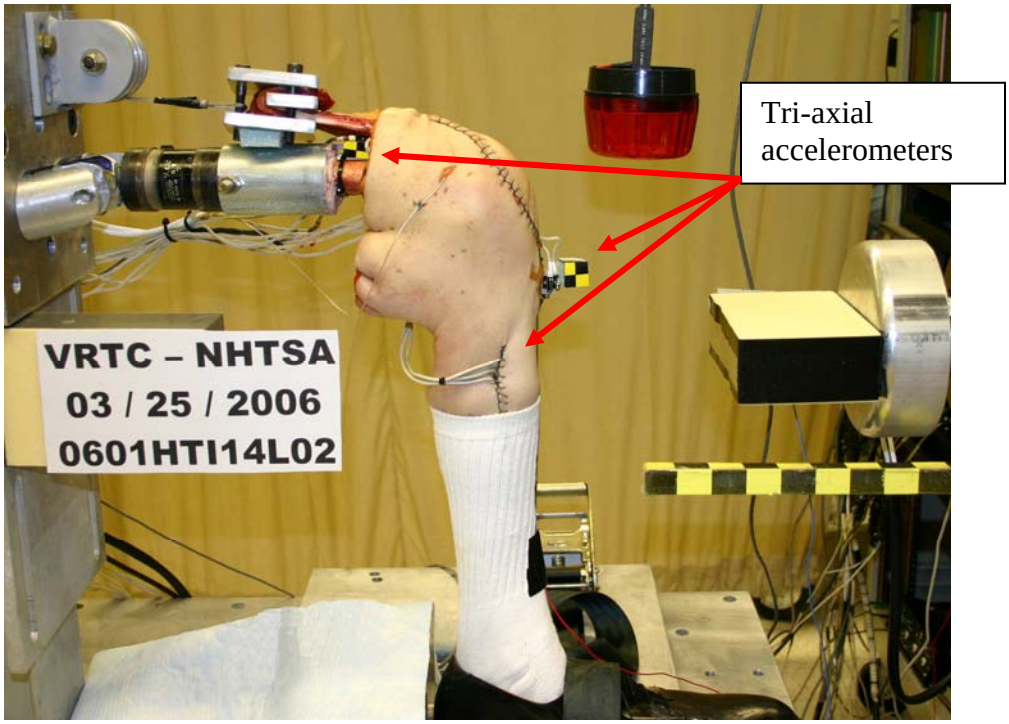


Figure 11: Group 2 Test Setup

After acquiring data during an impact, the acceleration traces were double integrated to calculate three dimensional displacement of the femur and tibia. The locations of the accelerometers, as well as, specific anatomical landmarks were digitized using a Faro Arm. This allowed the accelerometer signals from each test to be transformed into the coordinate system of the subject. The transformation process is discussed in detail in

section 5.4. High speed video of each test was recorded at 1000 frames/s. Using video analysis software (Image Express), the displacements recorded from the accelerometers were verified with displacements calculated using the high speed video and analysis software. After analyzing the DVRT readings from Test Group 1, it was determined that the medial band of the PCL experiences the greatest displacement. As a result, it was decided to only use one DVRT applied to the medial band of the PCL for Test Group 2. The foot of each subject was strapped down to the test platform to reduce vertical motion during the tests.

Test subjects 0503HTI, 0504HTI and 0505HTI were impacted at speeds of 2.9m/s and 4.7m/s. In an effort to further reduce vertical motion during testing, the knee flexion angle was reduced from 100^{o} to 90^{o} for tests 0505HTI, 0601HTI and 0602HTI. Again for comparison purposes, the patella of the subjects 0503HTIR and 0504HTIL were removed while the knee of subjects 0503HTIL and 0504HTIR were left intact. No significant difference was found in the DVRT readings of the dissected vs. the intact knee. It was found from previous research that suturing the DVRT bards to the PCL provided a repeatable PCL displacement measurement [8]. For tests 0601HTI and 0602HTI the barbs of the DVRT were sutured to the PCL as shown in Figure 12.

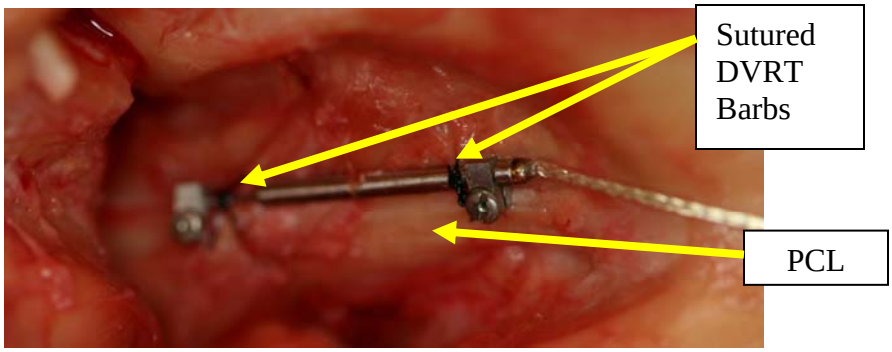


Figure 12: DVRT Barbs Sutured

The test conditions for the last four legs (two PMHS) of Test Group 2 were identical. The ACLs of all tested knees were removed to allow instrumentation of the PCLs. One DVRT was inserted in the medial band of the PCL and both barbs were sutured to the PCL. The quadriceps load was increased from 111N to 222N. It was believed that the 111N load had negligible effects that were being lost in the noise of the system. For test subjects 0601HTI and 0602HTI, each leg was impacted three times at 1.45m/s. The legs were impacted at this low speed to precondition the knee ligaments, and to provide a baseline knee response. After the three low energy impacts, the impact speed was gradually increased until failure was suspected. Injury was detected from; rapid drops in the DVRT plots or ram force, rapid increase in the rate at which the tibia displaced, physical inspection of the knee or visual inspection of the high speed video. Upon suspicion of injury, the legs were impacted at the initial 1.45m/s to evaluate the any changes from the baseline knee response. The test matrix for Group 2 is shown in Table 2.

Table 2: Group 2 Test Matrix

Test Subject	Impact Speeds (m/s)	Knee Status	Tibia Displacement Instrumentation Technique	Quad Load (N)	DVRT Attachment	Foot Strapped Down	Knee Flexion Angle
0503HTIL	2.9, 4.7	Intact	3 Tri-Axial Accels	111	Non-sutured	Yes	100º
0503HTIR	2.9, 4.7	Dissected	3 Tri-Axial Accels	N/A	Non-sutured	Yes	100º
0504HTIR	2.9, 4.7	Intact	3 Tri-Axial Accels	111	Non-sutured	Yes	90º
0504HTIL	2.9, 4.7	Dissected	3 Tri-Axial Accels	N/A	Non-sutured	Yes	90º
0505HTIR	2.9, 4.7	Dissected	3 Tri-Axial Accels	N/A	Non-sutured	Yes	90º
0601HTIL	1.45, 1.45, 1.45, 2.9,	Intact	3 Tri-Axial Accels	222	Sutured	Yes	90º
0601HTIR	1.45, 1.45, 1.45, 2.9,	Intact	3 Tri-Axial Accels	222	Sutured	Yes	90º
0602HTIL	1.45, 1.45, 1.45, 2.9, 3.2, 3.55, 3.9,	Intact	3 Tri-Axial Accels	222	Sutured	Yes	90º
0602HTIR	1.45, 1.45, 1.45, 2.9,	Intact	3 Tri-Axial Accels	222	Sutured	Yes	90º

Section 5.4 Data Processing

All signals were acquired using a 32-channel data acquisition system with a sampling rate of 20,000 Hz (Yokagowa Corporation of America). Each signal was zeroed and filtered according the specifications recommended by SAE J211. SAE J211 states the time should have a resolution of at least 1/100 s [9] and recommends filtering according to Channel Frequency Class (CFC). The CFC can be converted to a low-pass Butterworth filter. Refer to Table 3 for the conversion of CFC to Butterworth filter.

Table 3: CFC to Low-Pass Butterworth Filter

CFC	Equivalent Butterworth Filter Frequency (Hz)
60	100
180	300
600	1000
1000	1650

SAE J211 states that the forces and moments applied to the leg are to be CFC 600, while accelerations are to be CFC 1000. A sample data acquisition configuration sheet can be found in Appendix C. A program developed in house by The Vehicle Research and Test Center (VRTC) was used to filter, zero and perform mathematical operations on the acquired signals. Refer to Appendix D to view an example of the script file used to process the data.

To ensure the displacements of the tibia and femur were recorded in the coordinate system of the subject, the accelerometer coordinate system was transferred into the subject's coordinate system. The digitized three-dimensional point data from the impact location (Point A), one point on the anterior tibia (point B) and one point on the superior femur (point C) as shown in Figure 13, were used to create the subjects coordinate system. A list of all digitized points can be viewed in Appendix E.

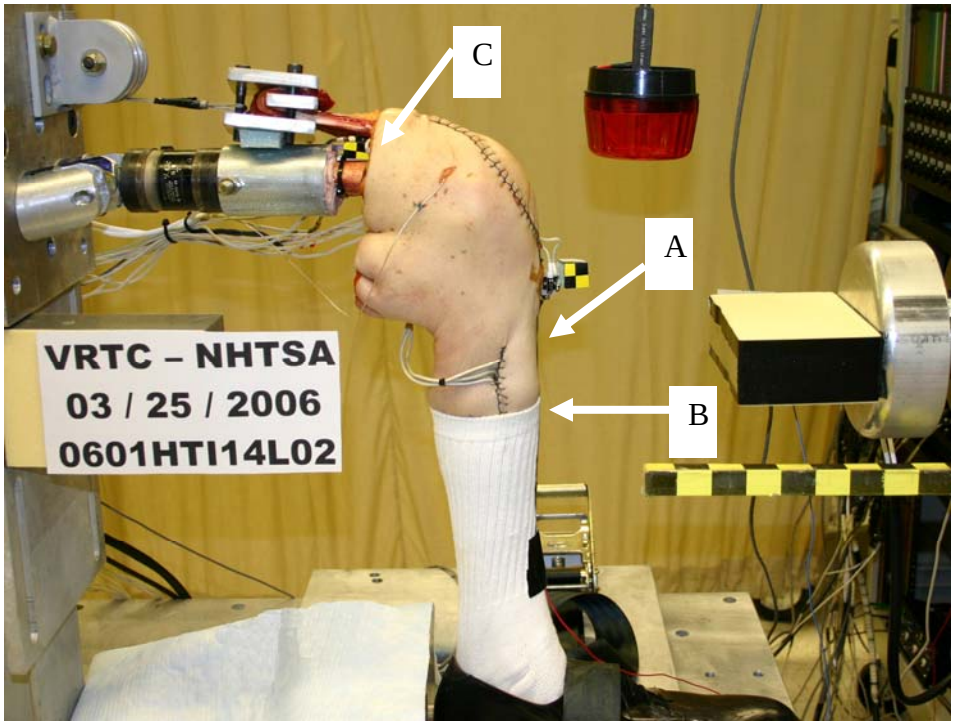


Figure 13: Subject Point Location

From these three points, one vector and two cross products were used to create the subject's global coordinate system. For all three accelerometer mounting blocks, three points were digitized, in a clockwise manor on the face of the accelerometer block, as shown in Figure 14. The yellow dots in Figure 14 represent the three point recorded by the Faro Arm. The red arrows in Figure 14 represent the directions in which each accelerometer is recording.

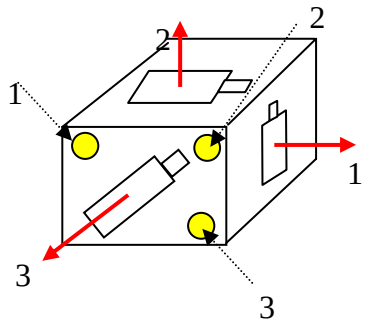


Figure 14: Accelerometer Block Point Digitization

Using the three points recorded on the block, two vectors and a cross were created to define the coordinate system of the accelerometer block. By knowing both the accelerometer block's coordinate system as well as the subject's coordinate system, the signals from each accelerometer block could be rotated into the coordinate system of the subject. This process of coordinate system transformation was adapted from Shaw et al [10]. Refer to Appendix F to view the MATLAB script files that was used in this project.

CHAPTER 6

RESULTS

Section 6.1 Results of Test Group 1

The age of test subjects 0501HTI and 0502HTI were 61 and 87 years old, respectively. Both subjects were males who did not suffer from osteoporosis. The subject's anthropomorphic data is shown in Table 4. Note that the test data was not normalized for each subject because the aim of this study is to evaluate the test instrumentation, not define an injury criterion or determine the biomechanical properties of the lower extremity.

Table 4: Test Group 1 Subject Information

PMHS ID	Age	BMD (g/cm^2)	Leg	Tibia Length (cm)	Cut Femur Length (cm)	Denubed Weight (kg)
0501HTI	61	1.143	Left	49.5	17.78	4.99
			Right	49.5	17.78	4.99
0502HTI	87	1.09	Left	47	17.78	4.54
			Right	47	17.78	4.54

The DVRTs do not measure the displacement of the entire PCL, rather they only measure a portion of the PCL's displacement. It was necessary to measure the PCL band length as well as the DVRT barb-to-barb insertion length. The signals from the DVRT could then be scaled appropriately to measure full PCL stretch. The PCL lengths and the DVRT barb-to-barb insertion lengths are shown in Table 5. The scaling factors used to determine total PCL stretch are also shown in Table 5.

Table 5: Test Group 1 PCL Information

PMHS ID	Leg	Anterior-Medial PCL band Length (mm)	Posterior-lateral PCL band Length (mm)	Medial Bar-to-Barb Insertion Length (mm)	Lateral Bar-to-Barb Insertion Length (mm)	Anterior-Medial DVRT Scaling Factor	Posterior-lateral DVRT Scaling Factor
0501HTI	Left	31	34	16.5	15	1.88	2.27
	Right	31	32	18	17	1.72	1.88
0502HTI	Left	34	35	17	18	2.00	1.94
	Right	33	34	17	18	1.94	1.89

The maximum tibia displacement and DVRT reading for all impacts in Test Group 1 are shown in Table 6. Injury occurred in tests 0501HTI35R04, 0502HTI49L02 and 0502HTI49R02 as shown in yellow on Table 6.

Table 6: Max tibia displacement and DVRT readings for Test Group 1

Test Number	Impact Speed (m/s)	DVRT Max (mm)		PCL Stretch (mm)		Max Tibia Displacements (mm)	
		Lat. PCL	Med. PCL	Lat. PCL	Med. PCL	Linear Potentiometer	Film
0501HTI33L01	3.33	1.25	1.31	2.55	2.70	22.1	N/A
0501HTI29R02	2.68	1.15	1.64	2.16	2.83	13.7	N/A
0501HTI33R03	3.14	1.25	1.79	2.35	3.09	16.1	N/A
0501HTI35R04	3.57	1.26	1.75	2.36	3.01	19.2	N/A
0501HTI43R05	4.32	0.63	1.14	1.18	1.95	23.7	N/A
0502HTI29L01	2.81	1.74	2.95	3.38	5.90	12.8	21
0502HTI47L02	4.77	1.36	2.13	2.65	4.26	30.9	50
0502HTI29R01	2.77	0.84	1.62	1.57	3.15	14.1	16.8
0502HTI47R02	4.80	0.70	1.99	1.32	3.87	27.5	46.8

The medial and lateral PCL band stretch for all impacts on subject 0501HTIL are shown in Figure 15. The max PCL displacement of 5.90mm occurs on test 0501HTI29L01at 31.6 ms.

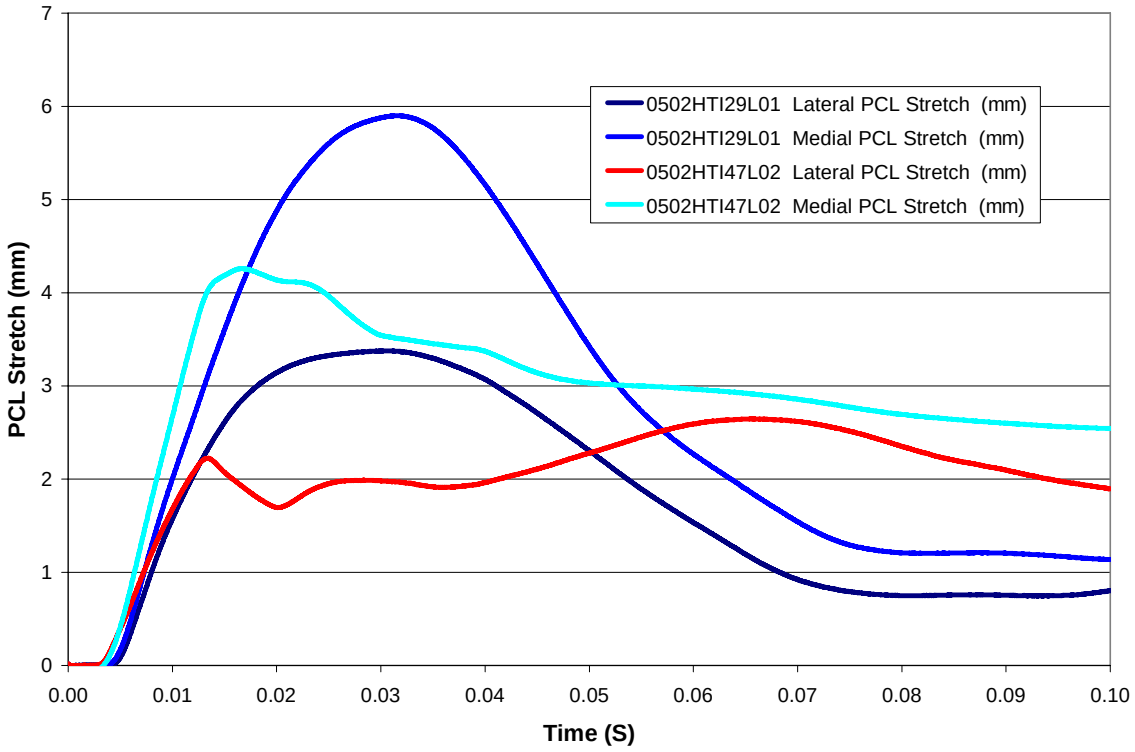


Figure 15: PCL stretch for all impacts on subject 0502HTIL

Along with PCL stretch, the femur force signal and high speed video were useful in determining the exact time of injury. The femur force signal for tests 0502HTI29L01 and 0502HTI47L01 are shown in Figure 16.

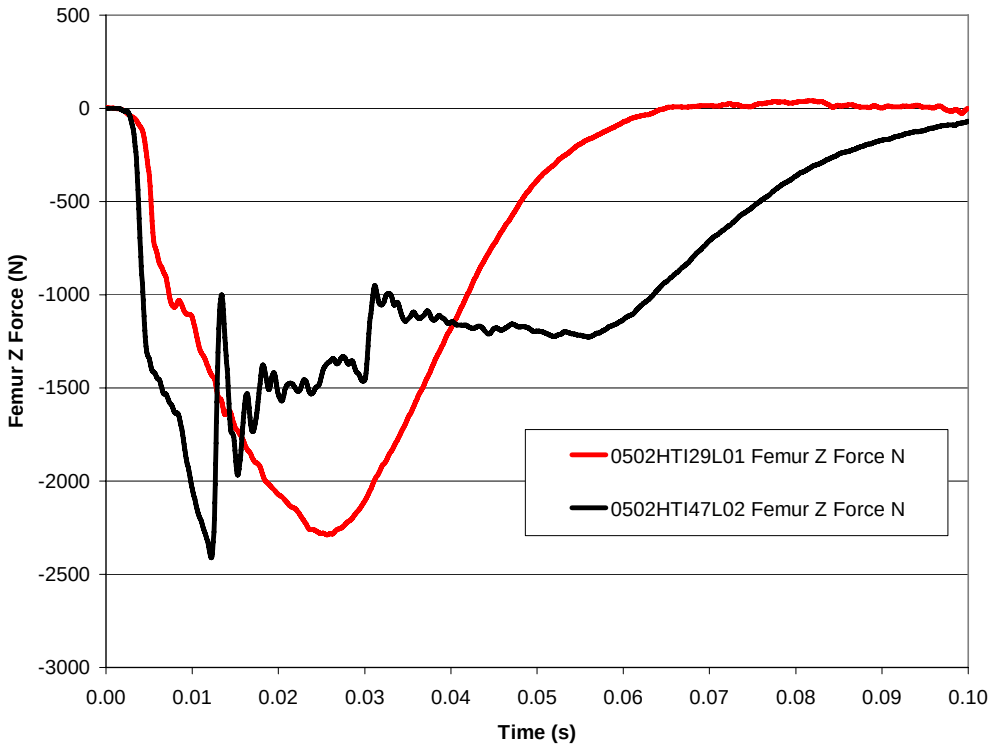


Figure 16: Femur Z Force vs. Time for All Impacts on Subject 0502HTIL

In Test Group 1, determining the exact time of injury proved to be difficult for tests 0502HTIR. After all desired tests were complete for a given PMHS leg, an autopsy was conducted to determine the type and degree of injury. The tibia displacement, time of injury and type of injury are for each subject in Group 1 are shown in Table 7.

Table 7: Test Group 1 Injury Results

Test Number	Tibia displacement at time of injury (mm)	Time of Injury (ms)	Injury
0501HTI35R04	17.32	23	Tibia and Fibula Fx emminating from posteior location of thru pin
0502HTI47L02	11.5	13	Tibia and Fibula Fx emminating from posteior location of thru pin
0502HTI47R02	Unknown	Unknown	Tibia and Fibula Fx emminating from posteior location of thru pin

Post-test MRI of subject 0502HTIR showed that the tibia fracture was emanating from the posterior location of the linear potentiometer thru pin as shown in Figure 17.

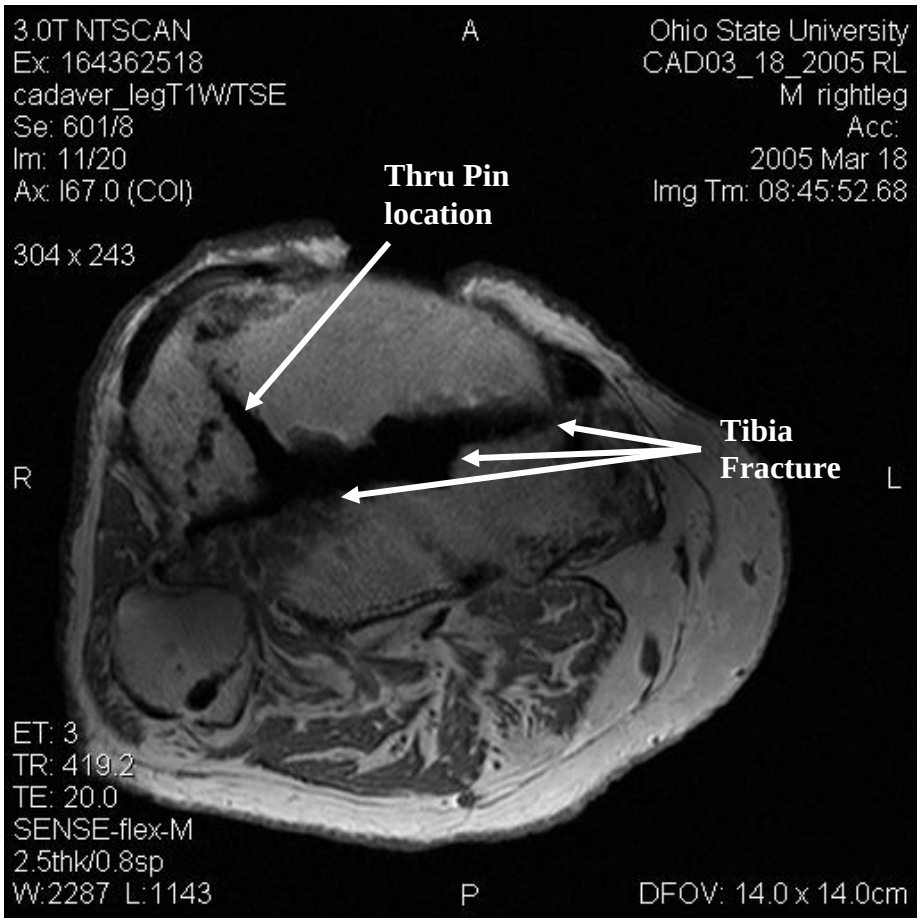


Figure 17: Post-Test MRI of Subject 0502HTIR

Section 6.2 Results of Test Group 2

The average age of test subjects in Group 2 was 71 years old. All subjects were male except PMHS 0601HTI and none of the subjects suffered from osteoporosis. The subject's anthropomorphic data is shown in Table 8. Note that the test data was not normalized for each subject because the aim of this study is to evaluate the test instrumentation, not define an injury criterion or determine the biomechanical properties of the lower extremity.

Table 8: Test Group 2 Anthropomorphic data

PMHS ID	Age	BMD (g/cm^2)	Leg	Tibia Length (cm)	Cut Femur Length (cm)	Denubed Weight (kg)
0503HTI	77	1.011	Left	35	17.78	3.63
			Right	35	17.78	3.63
0504HTI	87	1.149	Left	43	17.78	5.9
			Right	43	17.78	5.9
0505HTI	53	0.787	Left	N/A	N/A	N/A
			Right	39.6	17.78	5.44
0601HTI	74	1.056	Left	37.2	17.78	4.08
			Right	37.4	17.78	4.08
0602HTI	63	1.233	Left	43	17.78	5.44
			Right	43	17.78	5.9

As previously stated, the DVRTs do not measure the displacement of the entire PCL. However, they measure a portion of the PCL's displacement. The signals from the DVRT were appropriately scaled to measure full PCL stretch. The PCL lengths and the DVRT barb-to-barb insertion lengths for Group 2 are shown in Table 9. The scaling factors used to determine total PCL stretch are also shown in Table 9.

Table 9: Test Group 2 PCL Data

PMHS ID	Leg	Anterior-Medial PCL band Length (mm)	Posterior-lateral PCL band Length (mm)	Medial Bar-to-Barb Insertion Length (mm)	Lateral Bar-to-Barb Insertion Length (mm)	Anterior-Medial DVRT Scaling Factor	Posterior-lateral DVRT Scaling Factor
0503HTI	Left	39	38	17	17	2.29	2.24
	Right	35	35	16	17	2.19	2.06
0504HTI	Left	39	38	17	16	2.29	2.38
	Right	37	39	18	19	2.06	2.05
0505HTI	Left	N/A	N/A	N/A	N/A	N/A	N/A
	Right	29	31	17	N/A	1.71	N/A
0601HTI	Left	38	N/A	19	N/A	2.00	N/A
	Right	38	N/A	19	N/A	2.00	N/A
0602HTI	Left	40	N/A	19	N/A	2.11	N/A
	Right	40	N/A	20	N/A	2.00	N/A

The maximum tibia displacement and DVRT reading for all impacts in Test Group 2 are shown in Table 10. Injury occurred on tests 0503HTI29R01, 0504HTI47L02, 0504HTI47R02, 0505HTI32R03, 0601HTI29R04, 0601HTI29L04, 0602HTI29L04 and 0602HTI39R07, as shown in yellow on Table 10.

Table 10: Test Group 2 Test Results

Test Number	Impact Speed (m/s)	DVRT Max (mm)		Displacement From DVRT's Strain (mm)		Max Tibia Displacements From Accelelerometers (mm)
		Lat. PCL	Med. PCL	Lat. PCL	Med. PCL	Accel
0503HTI29R01	2.93	0.02	0.90	0.043	1.96	N/A
0503HTI29L01	2.95	1.80	3.35	4	7.68	25.5
0503HTI47L01	4.95	1.60	No sig	3.66	No sig	74.85
0504HTI29L01	2.80	0.72	1.09	1.69	2.51	31.1
0504HTI47L02	4.81	1.12	0.04	0.1017	2.56	119.45
0504HTI29R01	3.00	0.73	2.84	1.51	5.84	40.766
0504HTI47R02	4.81	5.96	No sig	12.25	No sig	79.266
0505HTI27R01	2.76	N/A	2.17	N/A	3.71	15.79
0505HTI29R02	2.84	N/A	2.28	N/A	3.90	19.2
0505HTI32R03	3.13	N/A	2.22	N/A	3.79	16.16
0601HTI14R01	1.30	N/A	1.42	N/A	2.84	13.99
0601HTI14R02	1.33	N/A	1.57	N/A	3.14	12.98
0601HTI14R03	1.32	N/A	1.66	N/A	3.32	12.82
0601HTI29R04	2.99	N/A	2.03	N/A	4.06	38.94
0601HTI14R05	1.46	N/A	2.14	N/A	4.28	24.21
0601HTI14L01	1.30	N/A	1.49	N/A	2.98	14.4
0601HTI14L02	1.33	N/A	1.38	N/A	2.76	15.32
0601HTI14L03	1.42	N/A	1.47	N/A	2.94	15.71
0601HTI29L04	2.89	N/A	1.62	N/A	3.24	32.32
0601HTI14L05	1.31	N/A	0.72	N/A	1.44	14.21
0602HTI14L01	1.46	N/A	1.90	N/A	3.80	9.29
0602HTI14L02	1.45	N/A	2.24	N/A	4.48	9.1
0602HTI14L03	1.43	N/A	2.2	N/A	4.40	8.588
0602HTI29L04	2.94	N/A	3.35	N/A	6.70	39.55
0602HTI14L05	1.39	N/A	2.95	N/A	5.90	26.6
0602HTI14R01	1.37	N/A	2.27	N/A	4.54	10.6
0602HTI14R02	1.57	N/A	2.52	N/A	5.04	12.23
0602HTI14R03	1.49	N/A	2.38	N/A	4.76	9.35
0602HTI29R04	2.93	N/A	3.46	N/A	6.92	17.78
0602HTI32R05	3.20	N/A	3.69	N/A	7.38	21.43
0602HTI35R06	3.48	N/A	3.79	N/A	7.58	25.82
0602HTI39R07	3.83	N/A	3.75	N/A	7.50	59.2
0602HTI14R08	1.44	N/A	4.33	N/A	8.66	28.28

After all tests were complete for a PMHS, an autopsy was conducted to determine the type and degree of injury. The tibia displacement at time of injury for all tests that could be deciphered is shown in Table 11. The type and time of injury for each subject in Group 2 are shown in Table 11.

Table 11: Test Group 2 Injury Information

Test Number	Tibia displacement at time of injury (mm)	Time of Injury (ms)	Injury
0503HTI29R01	15.7	15	Tibia planteon fracture at screw insertion from anterior tri-ax
0503HTI47L01	Unknown	Unknown	MCL and PCL avulsion
0504HTI47L02	39	15	LCL, MCL and PCL avulsion
0504HTI47R02	Unknown	Unknown	LCL, MCL and PCL avulsion
0505HTI32R03	16.1	23.3	Tibia fracture at anterior accel block location
0601HTI29R04	19.89	21	The PCL avulsed the center portion of proximal tibia with secondary fracture through midpoint of lateral tibia plateau
0601HTI29L04	17.43	18.4	The PCL avulsion where PCL attaches to tibia
0602HTI29L04	17.72	22.7	PCL tear across distal third
0602HTI39R07	24.69	22.7	PCL avulsion at tibia attachment

As mentioned in section 5.2 the linear potentiometer used to measure tibia displacement was causing pre-mature tibia fractures and was not recording accurate tibia displacement. As a result, three tri-axial accelerometers were used in place of the potentiometer. The tri-axial accelerometers were aligned, by hand, with the coordinate system of the test subject. The accelerometer signals were then transferred into the coordinate system using the method previously described. A comparison of the relative

tibia displacement in the x axis was made between the corrected and uncorrected accelerometer signals (Figure 18).

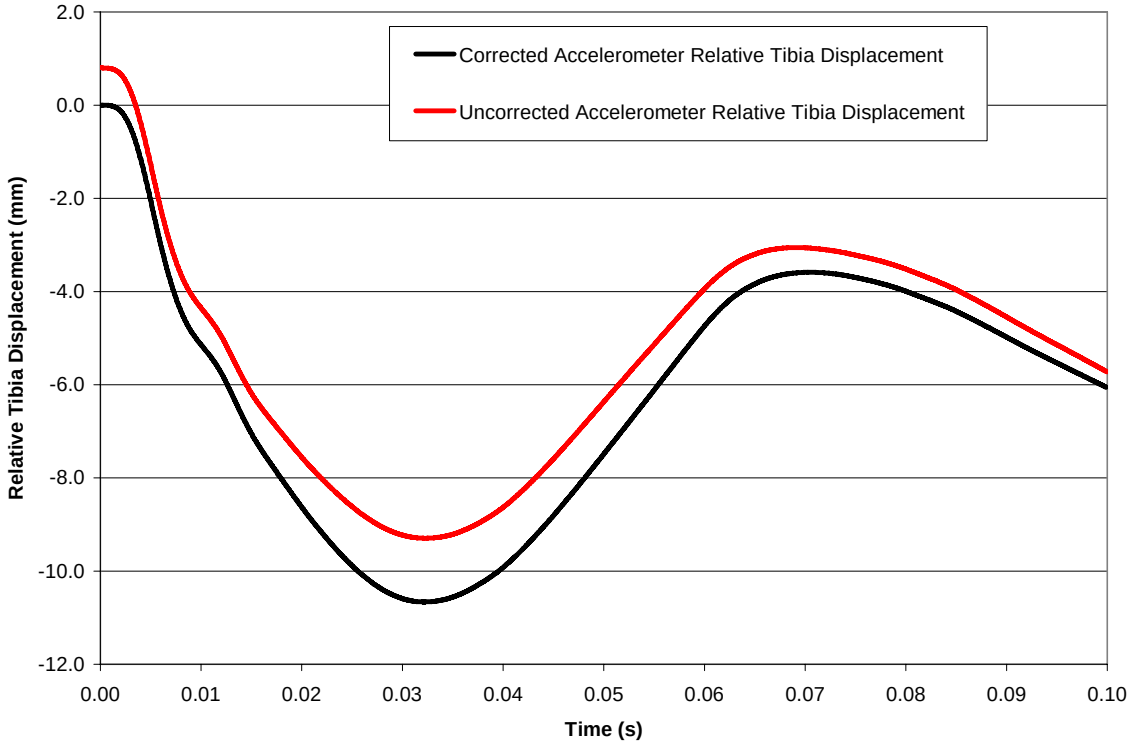


Figure 18: Comparison of Corrected vs. Uncorrected Accelerometer Tibia Displacement

Video analysis was used to ensure that the use of tri-axial accelerometers to find relative tibia displacement was a viable option. A comparison of the video analysis vs. the corrected accelerometer relative tibia displacement is shown in Figure 19.

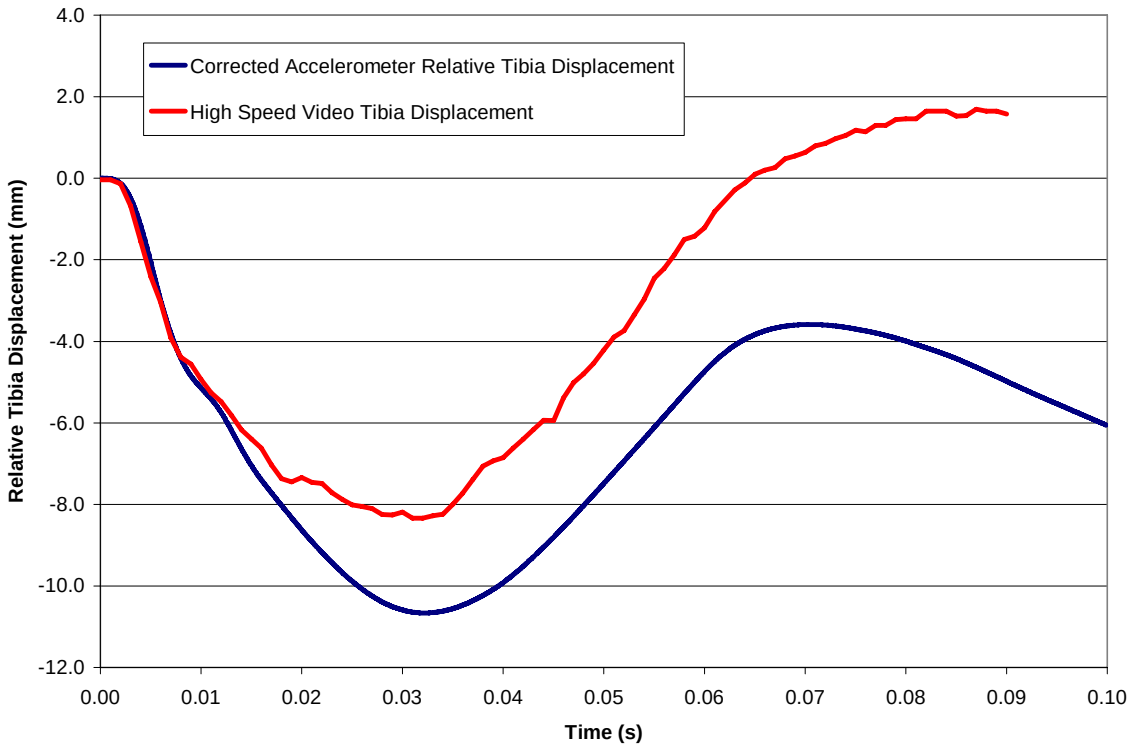


Figure 19: Tibia Displacement Measurement Comparison for Test 0602HTI14L01

All of the test data from tests 0601HTIL, 0601HTIR, 0602HTIR and 0602HTIL provided similar results. Therefore, data from 0602HTIL will be used as representative data for these four tests. The corrected relative tibia displacements for all impacts test subject 0602HTIL were overlaid to view the changes in measured tibia displacement for each impact. The overlaid tibia displacement measurements are shown in Figure 20.

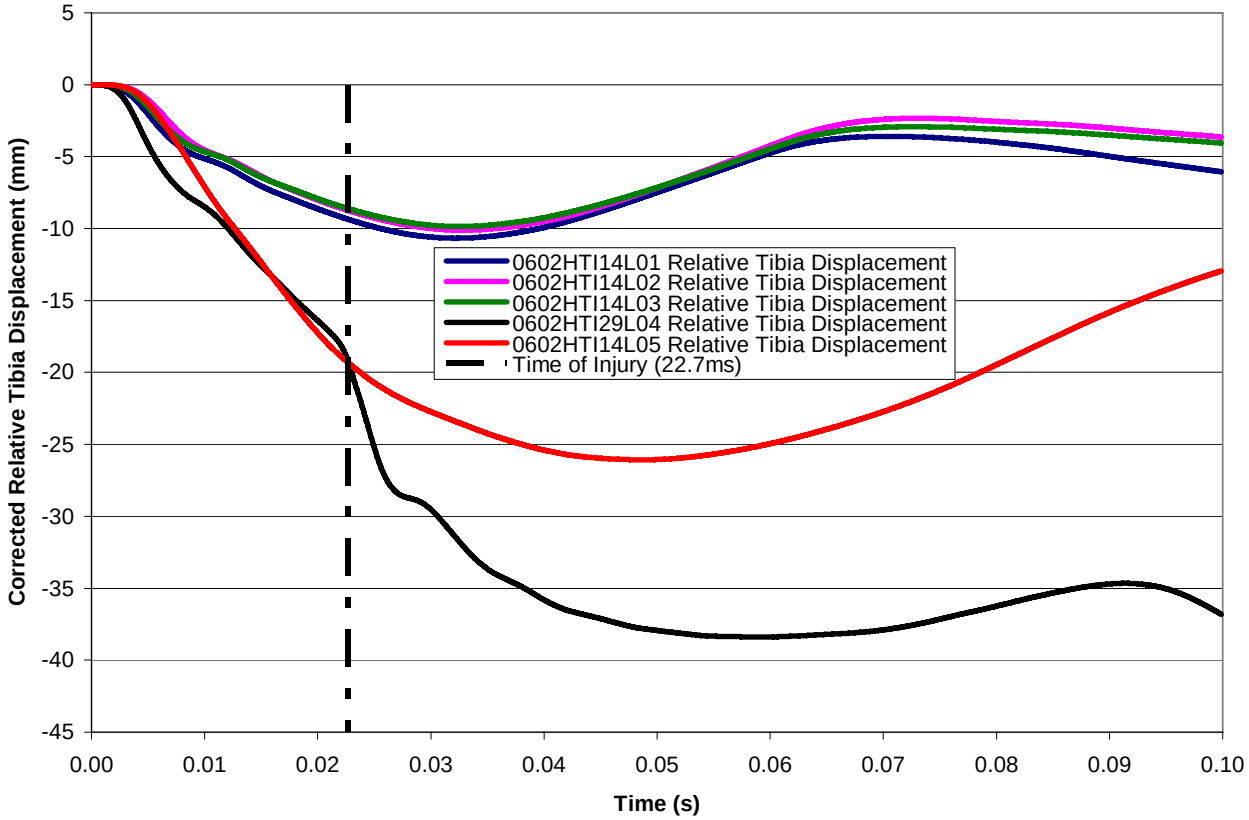


Figure 20: Corrected Relative Tibia Displacement for All Impacts on Left leg of Subject 0602HTI

The PCL stretch was also overlaid for each impact on the left leg of subject 0602HTI to view any change in PCL response for each impact. The PCL stretch measurements are shown in Figure 21.

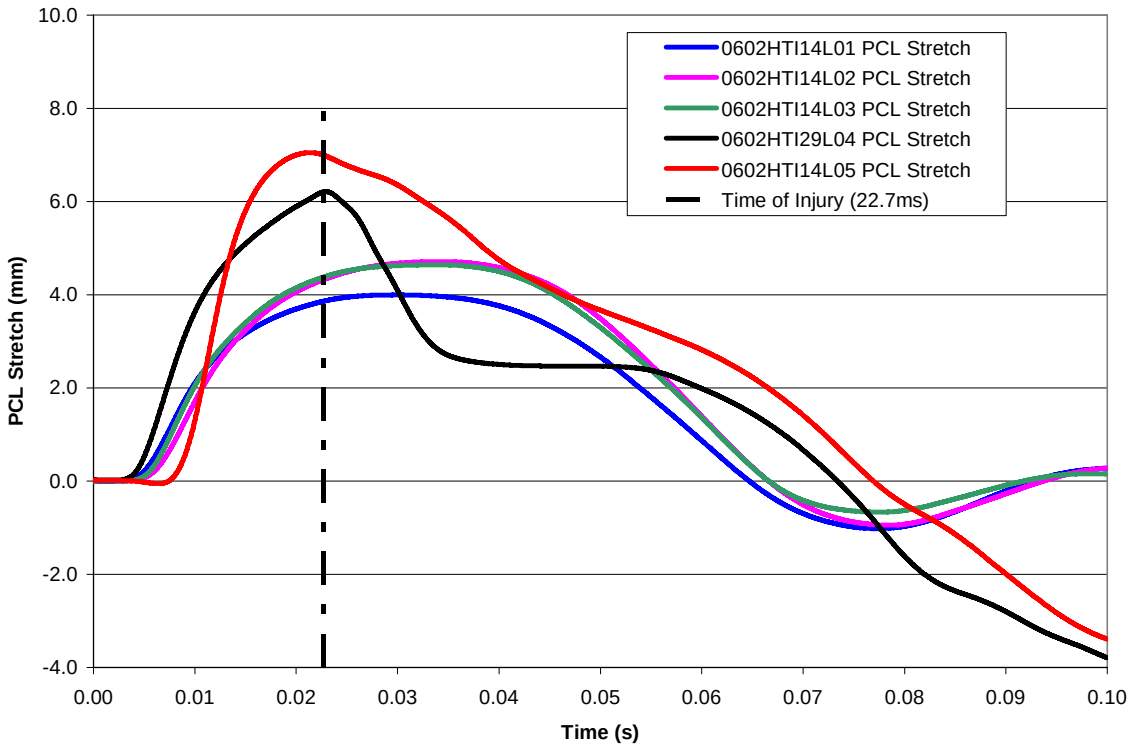


Figure 21: PCL Stretch for All Impacts on the Left Leg on Subject 0602HTI

The forces acting on the femur can give insight into the amount of force that is actually transmitted through the knee. Overlaying the femur forces in the z axis for each impact will provide information about any change in knee response during an impact or set of impacts. The femur forces in the z axis for all impacts on the left leg of subject 0602HTI are shown in Figure 22.

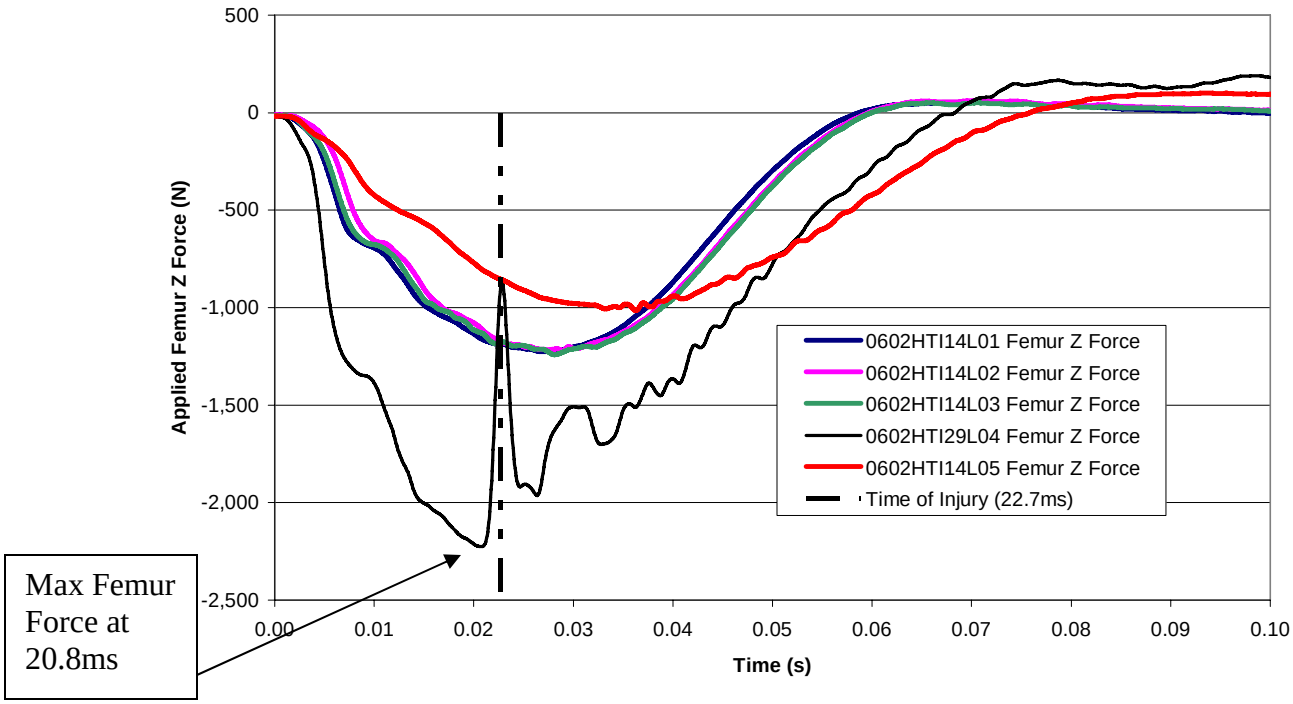


Figure 22: Applied Femur Z Force for All Impacts on the Left Leg of Subject 0602HTI

To investigate the PCL stretch signals in greater depth the derivative of the signal has been taken to observe any changes in the rate at which the PCL stretches. A change in PCL stretch rate is though to provide insight into the time of injury. The rate of PCL stretch for test impact 0602HTI29L04 is shown in Figure 23.

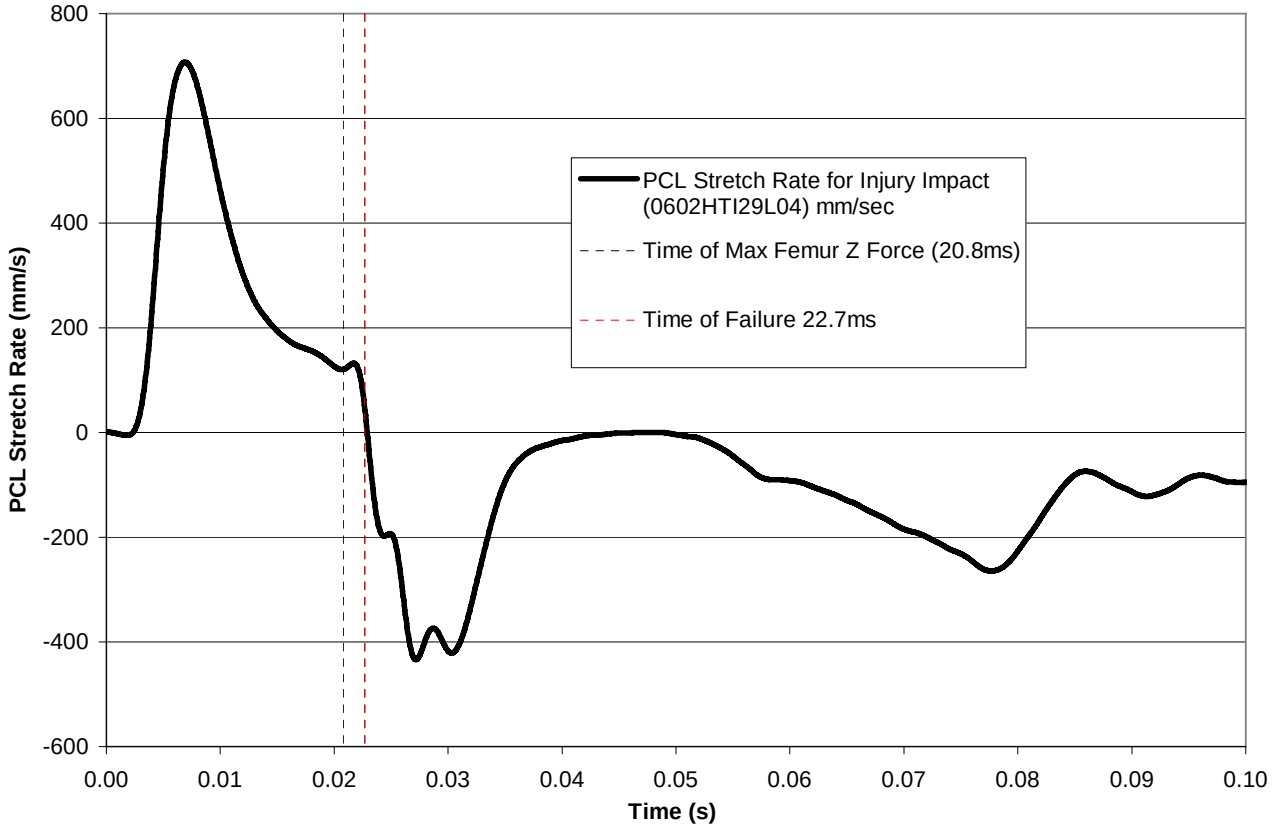


Figure 23: PCL Stretch Rate for Injury Impact 0602HTI29L04

CHAPTER 7

Discussion

Section 7.1 Test Group1 Discussion

As shown in Table 7 all of the injuries in Test Group 1 were tibia fractures. Tibia fractures were not expected to be the primary mode of failure in frontal tibial impacts. As shown in Figure 17, the post test MRI provided evidence that the tibia fractures were emanating from the posterior location of the linear potentiometer thru pin. It was also seen in the high speed test video that the linear potentiometer was bending, causing inaccurate tibia displacement readings. Therefore, it was concluded that another displacement measurement method would have to replace the potentiometer. As stated previously, Test Group 2 used three tri-axial accelerometers in place of potentiometer.

For Test Group 1, time of injury was determined using three methods; PCL stretch plots, femur force plots and high speed video. As shown in Figure 15, the PCL displacement abruptly decreases at 13ms. This abrupt drop in PCL Stretch indicates an injury has occurred. The same can be seen in Figure 16, where the femur force rapidly drops 1,300 N at 13ms. This rapid reduction in applied femur force indicated that the knee is no longer able to transmit force from the tibia to the femur, indicating a failure has occurred. During analysis of the high speed video, a change in tibia displacement can be seen at 13ms confirming an injury has occurred.

During analysis of Test Group 1 it was observed that the medial band of the PCL always experiences greater displacement as shown in Table 6. As a result it was hypothesized that one DVRT applied to the medial band of the PCL would provide better

measurements, due to the limited space inside the knee joint. A decision was made to use one DVRT in the medial band of the PCL for all subjects in Test Group 2.

Section 7.2 Test Group 2 Discussion

Initially the anterior tibia accelerometer was screwed to the tibia. As seen in Table 11, test 0503HTI27R01 resulted in a tibia fracture emanating from the accelerometer block screw location. After test 0503HTI27R01, the anterior tibia accelerometer block was glued to the bone. Gluing the block to the bone provide a strong attachment without jeopardizing the structural integrity of the tibia. The time of failure for bone fractures was determined for all tests in Group 2. However, determining the time of failure for ligament injuries initially proved to be more difficult. It was found that suturing the DVRT to the ligament provided repeatable PCL displacement measurements. It is believed that suturing the DVRT to the PCL also provided more sensitivity to changes in PCL response.

After the accelerometer signals were transformed into the coordinate system, a comparison of the corrected vs. the uncorrected tibia displacements was completed to view any changes in measurements. It is expected, that since the accelerometers are already approximately in the subjects coordinate system, that there would be a minimal change in displacements. As shown in Figure 18, the corrected accelerometer signals follow the exact trends as the uncorrected signal only with greater magnitude in the x axis.

A comparison of the corrected accelerometer signals and the high speed video analysis was completed to determine how similar the two methods measured

displacement. As shown in Figure 19, the accelerometers measured a greater magnitude in tibia displacement. Although the magnitude is greater, the two methods followed the same trends in displacement. It is believed that double integration of the corrected accelerometer signals provides more accurate measurements of tibia displacement for these short duration tests. If the high speed camera is not exactly perpendicular to the tibia x axis, any displacement measurements obtained from video analysis can be inaccurate.

After the method of using tri-axial accelerometers to calculate displacement was validated, it was found that the displacement measurements could be used to find time of injury. As shown in Figure 20 on impact 0602HTI29L04, the rate at which the tibia displaces abruptly increases at 22.7ms indicating an injury has occurred. The tibia displacement measurements also show that the post-injury knee response (0602HTI14L05) differs greatly from the base line knee response (0602HTI14L01, 0602HTI14L01, 0602HTI14L01), indicating the structural integrity of the knee has indeed has been jeopardized.

As stated previously time of injury can also be determined using high speed video, PCL stretch and applied femur force. As seen in Figure 21, the second (0602HTI14L01) and third (0602HTI14L01) impacts provide a repeatable baseline knee response. A rapid drop in PCL displacement at 22.7ms can be seen in the fourth impact, (0602HTI29L04) thus, indicating an injury has occurred.

A 1,500 N drop in applied femur force occurs at 20.8ms, which is 1.9ms prior to 22.7ms as shown in Figure 22. It is believed that the ligament injuries can occur over a period of 2-3ms. The force begins to drop as microscopic tears in the ligament begin to

take place. The indication of injury happening over this 2ms time period can be seen in the rate of PCL stretch as shown in Figure 23. Figure 23 shows that at 20.8ms, the rate at which the PCL stretch begins to increase indicating the initiation of microscopic injury. The failure of the ligament does not occur until 2ms later when the PCL stretch rate becomes negative. This indicates relaxation of the PCL produced from the complete failure of the ligament, as shown in Figure 23. It is also observed that in the post injury impact (0602HTI14L05), the knee does not posses the same ability to transmit force to the femur as in the pre-injury impacts (0602HTI14L01, 0602HTI14L01, 0602HTI14L01).

Using one DVRT sutured to the medial band of the PCL, provided repeatable PCL displacement measurements and greater sensitivity to changes in PCL response. The use of tri-axial accelerometers to find displacement provided accurate tibia displacement measurements in three dimensions. After implementing the tri-axial accelerometers and suturing the DVRT to medial band of the PCL, time of injury was determined for ligament and bone injuries.

Now that the time of injury for tibia and PCL failures can be determined and the relative tibia displacement can be accurately measured, the next step in this research is to start removing the constraints initially placed on the test setup. Removing the constraints placed on the test setup will provide a more “real world” situation allowing future researchers to obtain the biomechanical properties of the knee in a frontal car crash. To create a test matrix that will allow efficient investigate of the biomechanical properties of the knee, sufficient modeling should be conducted to evaluate the sensitivity of each test parameter. As a result of the sensitivity analysis, researchers will be able to reduce

variation while still providing a real world test setup. Using the measurement instrumentation developed in this research, investigators will be able to obtain test data that can be used to develop a more biomechanical based knee slider criterion and tibia displacement injury index.

CHAPTER 8

CONCLUSION

- Suturing the DVRT barbs to the PCL provided repeatable PCL displacement measurements

- The time of failure was identified for both bone and ligament injuries

- After correction, the use of tri-axial accelerometers provide accurate tibia displacement measurements

REFERENCES:

1. Atkinson, PJ, Atkinson, T. (2000). Knee injuries in motor vehicle collisions: a study of the national accident sampling system database for the years 1979-1995. Acc Anal Prev, 32:779-786.,
2. Hendrie, D., Rosman, D., Harris, A., 1994. Hospital inpatient cost resulting from road crashes in Western Australia. Aust. J. Public Health 18, 380-388,
3. Miller, T., Lestina, D., Spiler, R., 1998. Highway crash cost in the United States by driving age, blood alcohol level, vitim age and restraint use. Accid. Anal. Prev. 30, 137-150
4. Viano, DC, Culver, CC, Haut, RC, Melvin, JW, Bender, M, Culver, RH, Levine, RS. (1978). Bolster impacts to the knee and tibia of human cadavers and an anthropomorphic dummy. Proceedings of the 22nd Stapp Car Crash Conference, Society of Automotive Engineers, Paper 780896.
5. Balasubramanian, S., Beillas, P., Belwadi, A., Hardy, W.N., Yang, K.H., King, A.I. (2004). Below knee impact responses using cadaveric specimens. Stapp Car Crash Journal, Vol. 48 (November 2004), pp. 71-88,
6. Bartsch, A, Litsky, A, McFadden, J, Herriot, R (2004) Posterior cruiciate ligament response to proximal tibia impact, Masters Thesis, The Ohio State University,
7. Butler, DC, Noyes FR, Grood, ES (1977). Ligamentous contributions to AP stability of the knee. Biomechanics Symposium-AMD, 23:217-220.
8. Markolf KL, Willems MJ, Jackson SR, Finerman GA. In situ calibration of miniature sensors implanted into the anterior cruciate ligament part I: strain measurements.J Orthop Res. 1998 Jul;16(4):455-63.
9. SAE Publication, SAE J211 – Instrumentation for Impact Test, SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001
10. Shaw, JM., Biomechanical Response of the Human Thorax to Oblique and Lateral Impacts, Masters Thesis, The Ohio State Univeristy, 2005.
11. The Netter Presenter: Human Anatomy Collection Version 2.0, Icon Learning System, LLC, Teterboro, NJ

APPENDIX

A. PMHS Selection Algorithm

Proximal Tibia Specimen Selection Protocol

Subject Number:_____

Test Date:_____

General Selection Criteria:

1. The subject must have a date of death within the previous 36 hours such that testing is completed within 60 total hours.

2. The cadaver must have at least 10 inches of femur proximal to femoral condyles.

3. The cadaver must be at least 18 years of age.

4. The cadaver must not be broader than 23 inches at the shoulder or have a chest depth of greater than 17.5 inches (*MRI limiting factor if full body.)

5. The cadaver must be free of HIV/AIDS.

6. The cadaver must have no indication of serious knee anatomical or mechanical deficiencies. [Examples include: obvious surgical scarring anterior knee, total knee replacement, ligament injury/surgery, meniscus injury/surgery, cartilage injury/surgery, tibial plateau/shaft fracture, femoral condyle/shaft fracture, patella fracture, talus/calcaneus fracture, severe osteoporosis/osteoarthritis and clinically significant knee laxity.]

7. The subject must be deemed fit by Dr. Litsky, John Bolte, Mark Whitmer or score at least **+2** on the Cadaver Selection Algorithm.

Scoring System
Age
Height
Time since death

Weight
Pre-Existing Conditions:

Scoring System:

Age		**Time since death**	
<18 years of age	NO-GO	<12 hours since death	1
18-30 years of age	8	12-24 hours since death	1
31-40 years of age	6	24-36 hours since death	0
41-50 years of age	4	>36 hours since death	NO-GO
51-60 years of age	3		
61-70 years of age	1		
71-80 years of age	0		
81-90 years of age	0		
91-100 years of age	NO-GO		
100+ years of age	NO-GO		
Height *Isolated Leg Dimensions Not Considered*		**Weight**	
Between 60 and 65 inches	0	Between 100 and 200 pounds	1
		>200 pounds	0
		<100 pounds	0
Between 65 and 75 inches	1	Between 125 and 250 pounds	1
		>250 pounds	0
		<125 pounds	0
Between 76 and 80 inches	0	Between 150 and 300 pounds	1
		>300 pounds	NO-GO
		<150 pounds	0
>80 inches	NO-GO	>300 pounds	NO-GO
<60 inches	NO-GO	<100 pounds	NO-GO
Pre-Existing Conditions:			
Scarring (anterior knee)		**Tibial Fracture**	
Severe (surgical)	NO-GO	Malunion or Non-Union	NO-GO
Moderate	-2	Past	-2
Mild	-1	**Patellar Fracture**	
None	0	Malunion or Non-Union	NO-GO
Total Knee Replacement	NO-GO	Past	-1
Ligament Injury		**Femoral Fracture**	
ACL	NO-GO	Malunion or Non-Union	NO-GO
PCL	NO-GO	Past	-2
MCL	NO-GO	**Talus Fracture**	
LCL	NO-GO	Malunion or Non-Union	-2
No previous ligamentous injury	0	Past	-1

Ligament Surgery		**Calcaneus Fracture**	
ACL	NO-GO	Recent	-1
PCL	NO-GO	Past	-1
MCL	NO-GO	**Femur length available**	
LCL	NO-GO	>10 inches proximal to patella?	1
No previous ligament surgery	0	8-10 inches proximal to patella?	0
Meniscus Injury		<8 inches proximal to patella?	NO-GO
Recent	-1	**HIV Test**	
Past	-1	Positive	NO-GO
Cartilage Injury		Negative	0
Recent	-1	**Hepatitis Test**	
Past	-1	Positive	-2
Knee Laxity (Posterior Drawer)		Negative	0
Grade I	0	**Bone Density Test (Radiologist/Phalanges/DEXA?)**	
Grade II	-4	Poor	-5
Grade III	NO-GO	Below Average	-3
Osteoporosis		Average ***(Based on 65 Years of Age)***	0
Mild	0	Above Average	4
Moderate	-2		
Severe	-4		

Lower Extremity Dimensions (Anthropometric Source Book, Volume 1: Anthropometry for Designers. NASA Reference Publication 1024, July 1978, National Aeronautics and Space Administration):

Male- Tibia Length = 0.268*stature-8.369 (+/- 1.33) (cm)
Fibula Length = 0.257*stature-6.490 (+/- 6.49)
50th male: Tibia=39.07 Fibula = 39.00

Female- Tibia Length= 0.242*stature-4.870 (+/- 1.15) (cm)
Fibula Length = 0.243*stature-4.695 (+/- 1.13)
50th female: Tibia=34.72 Fibula = 35.06

B. Sample Test Checklist

Proximal Tibia Impact Test Procedure Checklist

TEST #: _____ DATE: _____

Notification Phase:

1. ___Mark Whitmer contacts Dr. Bolte and reports that cadaver/lower extremity(s) is/are available.
2. ___Enact cadaver selection algorithm-determine if cadaver is suitable for test (may not be 100% effective in all cases.)
3. ___Determine Preparation and Test Schedule.
4. ___Contact Team Members (Alan Litsky_____, Rod Herriott_____, Petra Schmalbrock-MRI_____, Mark Whitmer_____, John Bolte_____, Kiel Pfefferle_____,Joe McFadden_____, Herman Joos_____, Mike Dodge/Rachel Rush-X-Ray_____ and John Landoll-Bone Densiometry_____) and alert to testing course of action.
5. ___Schedule and record pre/post-test MRI time with Petra Schmalbrock.
6. ___Schedule and record X-ray pre/post-test time with Mike Dodge/Rachel Rush.
7. ___Schedule and record bone densiometry test time with John Landoll.
8. ___Schedule cadaver pickup with gurney from Mark Whitmer in morgue.
9. ___Schedule collection of blood with John Bolte
10. ___Obtain biohazard bags and boxes from loading dock in Graves Hall, determine and note if cadaver is save/no-save ashes.
11. ___Turn on power to cooler such that it is sufficiently chilled in time to receive lower extremity(s).
12. ___Check charging of batteries in lab, change out of drill/driver if necessary.
13. ___Contact livery services/dispatch transport vehicle from VRTC to appropriate location – if lower extremity(s) is/are received from outside of The Ohio State University.
14. ___Gather all supplies and equipment from OSU and VRTC including faro arm (if needed-See Tool Supply List.)
15. ___Meet at Room 3024 Graves Hall at assigned times.
16. ___Sign in OSHA Access Log **(Refer to Engineering Control Plan.)**

Cadaver Preparation:
(See Cadaver Selection & Preparation Protocol)
(Events occur in the Morgue)

(**R/L)**

1. ___/__ Ensure that universal precautions are being enforced at all times (proper personal protective equipment, blood-borne pathogen procedures and proper lab techniques used.)
2. ___/__ Wash lower extemity(s) with antiseptic soap and 10% bleach solution.

3. ___/__ Exercise lower extremity(s) through normal range of motion to remove rigor mortis.
4. ___/__ Examine subject lower extremity(s) for anomalies, bruises, abrasions, cuts and scars.
5. ___/__ Draw blood for HIV and Hepatitis tests and send to lab 3rd floor Doan Hall, 410 W. 10th Ave.
6. ___/__ Label each foot with a "R" or "L" to signify right or left leg respectively.
7. ___/__ Record lower extremity(s) anthropometric measurements (see Anthropometry Protocol.)
8. ___/__ Remove lower extremity(s) from subject at pelvis, making sure to remove femur in one section.
9. ___/__ Record subject information (cadaver number, height, weight, cause of death, age, and gender on data sheet.)
10. ___/__ Wrap in plastic for transport to imaging facility-place in cooler in 3024 Graves Hall if needed.

Pre-MRI & X-Rays (approximately 2+ hours):
(See MRI/X-Ray Protocol)

(**R/L)**

1. ___/__ Transport lower extremity(s) in proper bag, sheets and gloves to imaging facility outsideof Means Hall.
2. ___/__ Prepare MRI device for lower extremity(s) using knee coil and towels for bracing.
3. ___/__ MRI scan(s) on knee(s) per protocol from Petra Schmalbrock. Check for cruciate and collateral ligament continuity, meniscus quality and cartilage quality.
4. ___/__ Record saved file name and specify whether right or left leg for file retrieval.
5. ___/__ Disinfect the MRI machine.
6. ___/__ Transport lower extremity(s) to x-ray facility in Rhodes Hall.
7. ___/__ Prepare the x-ray machine.
8. ___/__ 1st x-ray anterior-posterior view.
9. ___/__ 2nd x-ray medial-lateral view.
10. ___/__ Record x-ray file names and session number for file retrieval (specify whether right or left.)
11. ___/__ Transport the lower extremity(s) to room 3024 Graves Hall and place in cooler.
12. ___/__ Check previous section for completion of all steps.

Cadaver Instrumentation:
(See Instrumentation Protocol)

(Left Leg)

1. ___Perform manual drawer tests (A-P) and medial-lateral laxity tests; record results.

2. ___On gurney/table, cut femur, leaving approximately 6-8 inches from patella. Save cut femur (must have femoral head and neck and 1-2" distal to lesser trochanter cleaned of flesh) and take sample for bone densiometry.
3. ___Smooth anterior accel location, glue accel block and secure with wire tie, allow to dry over night
4. ___Remove muscle and fascia from proximal 2-4 inches of femur in preparation for potting.
5. ___ Dissect quadriceps, leaving all of rectus femoris muscle. Pack muscle in moist gauze.
6. ___Clean and dry femur bone(s) for proper bonding.
7. ___Weigh the lower extremity(s) without shoe (See Pre-Test Data Protocol.)
8. ___Remove fat and synovial membrane surrounding ACL and PCL.
9. ___Separate ACL from PCL and remove ACL.
10. ___Record PCL length.
11. ___Prepare DVRT with barbs at determined distance from each other.
12. ___Check continuity of system, mark nonsensing end of core and cut core to proper length.
13. ___Prepare digital cameras and initiate still photos during insertion of DVRT's for documentation.
14. ___Attach one DVRT to the medial band of PCL. Place sensor end as deep in posterior knee as possible, in line with Anteromedial PCL fibers and connect with core. Make sure wire has some relief so as not to damage leads during testing. **Suture barbs to PCL**
15. ___Note which serial number corresponds to which DVRT
16. ___Note barb-barb inserted distance in PCL.
17. ___Perform anterior and posterior drawer tests to ensure free movement of DVRT core, re-insert DVRT if necessary.
18. ___ Suture exposed flesh and cover to prevent leaking during potting.
19. ___Clean lower extremity with antiseptic solution to remove blood.
20. ___Put on foot coverings.
21. ___Bring lower extremity into place near fixture.
22. ___Mix body filler with hardener.
23. ___Pot exposed femur in steel cup with body filler securing in place. **Make certain thigh and leg are vertical and in line with impactor. Foot is to lie flat on foot plate.**
24. ___Wait 5 minutes for body filler to harden completely.
25. ___Attach Femoral tri-axial accelerometer
26. ___Attach anterior tibial tri-axial accelerometer.
27. ___Mark medial tibial tri-axial accelerometer location at **1cm superior to impact location on medial side of the leg,** ensuring structural integrity of MCL is not jeopardized
28. ___Attach medial tibial tri-axial accelerometer
29. ___Ensure all accelerometer wires have some relief so as not to damage leads during testing.
30. ___Attach photo-target pins to tibia.
31. ___ Strap foot down to table

32. ___Take all required positional and anthropometric measurements (Pre-Test Positioning Measurements sheet).
33. ___Remove and dispose of protective clothing, wash hands, and put on new protective equipment.
34. ___Check previous section and all measurement sheets for completion of all steps.
35. ___Make sure all faro arm measurements are saved

Test Performance Phase and Positioning:
(See Positioning & Instrumentation Measurements Protocol)

(Left leg)

1. _/_/_/_/_Ensure that universal precautions are being enforced.
2. _/_/_/_/_Make sign board.
3. _/_/_/_/_Configure Yokogawa data acquisition system (See Yokogawa Operating Instructions.)
4. _/_/_/_/_Set-up high speed camera and lighting and flash.
5. _/_/_/_/_Place padding on impactor face.
6. _/_/_/_/_Clean impactor ram and lubricate the shaft.
7. _/_/_/_/_Check connection of ram accelerometer, tibial and femoral accelerometers, and light traps.
8. _/_/_/_/_Check positioning to ensure free flight of the ram.
9. _/_/_/_/_Raise the impact table to align the tibial tubercle with top edge of impact interface.
10. _/_/_/_/_Record the distance from the cameras to the tibial photo target.
11. _/_/_/_/_Connect all instrumentation, verify continuity, balance, etc.
12. _/_/_/_/_Position event tape on foam and lower extremity; hook up event switches.
13. _/_/_/_/_Zero all recording channels.
14. _/_/_/_/_Zero light trap reading.
15. _/_/_/_/_Double check photographic targets.
16. _/_/_/_/_Place inch tape in field of view for photographic analysis.
17. _/_/_/_/_Place sign board.
18. _/_/_/_/_ Apply quad load (50 Lbs)
19. _/_/_/_/_Still photography.
20. _/_/_/_/_Final camera focus.
21. _/_/_/_/_Ensure all test data sheets are complete (See Test Data Protocol.)
22. _/_/_/_/_Double check impactor height-avoid impact of photo targets.
23. _/_/_/_/_**TURN FLASH ON.**
24. _/_/_/_/_Check previous page for completion of all steps.
25. _/_/_/_/_Conduct test, fire impactor.
26. _/_/_/_/_Check knee, data and video for injury before next test

Cadaver Instrumentation:
(See Instrumentation Protocol)

(**Right Leg)**

1. ___Perform manual drawer tests (A-P) and medial-lateral laxity tests; record results.
2. ___On gurney/table, cut femur, leaving approximately 6-8 inches from patella. Save cut femur (must have femoral head and neck and 1-2" distal to lesser trochanter cleaned of flesh) and take sample for bone densiometry.
3. ___ Smooth anterior accel location, glue accel block and secure with wire tie, allow to dry over night
4. ___Remove muscle and fascia from proximal 2-4 inches of femur in preparation for potting.
5. ___Dissect quadriceps, leaving all of rectus femoris muscle. Pack muscle in moist gauze.
6. ___Clean and dry femur bone(s) for proper bonding.
7. ___Weigh the lower extremity(s) without shoe (See Pre-Test Data Protocol.)
8. ___Remove fat and synovial membrane surrounding ACL and PCL.
9. ___Separate ACL from PCL and remove ACL.
10. ___Record PCL length.
11. ___Prepare DVRT with barbs at determined distance from each other.
12. ___Check continuity of system, mark nonsensing end of core and cut core to proper length.
13. ___Prepare digital cameras and initiate still photos during insertion of DVRT's for documentation.
14. ___Attach one DVRT to the medial band of PCL. Place sensor end as deep in posterior knee as possible, in line with Anteromedial PCL fibers and connect with core. Make hole for lead wire to exit knee. Make sure wire has some relief so as not to damage leads during testing. **Suture DVRT barbs to PCL**
15. ___Note which serial number corresponds to DVRT
16. ___Note barb-barb inserted distance in PCL.
17. ___Perform anterior and posterior drawer tests to ensure free movement of DVRT core, re-insert DVRT if necessary.
18. ___Suture exposed flesh and cover to prevent leaking during potting.
19. ___Clean lower extremity with antiseptic solution to remove blood.
20. ___Put on foot coverings.
21. ___Bring lower extremity into place near fixture.
22. ___Mix body filler with hardener.
23. ___Pot exposed femur in steel cup with body filler securing in place. **Make certain thigh and leg are vertical and in line with impactor. Foot is to lie flat on foot plate.**
24. ___Wait 5 minutes for body filler to harden completely.
25. ___Attach Femoral tri-axial accelerometer
26. ___Wrap cut end of thigh to prevent splatter of tissue/fluid during impacts.
27. ___Clamp patellar tendon to belt strap for tendon tension-tension to minimum force to raise foot prior to impact (approximately 50 Lbs.)
28. ___Attach anterior tibial tri-axial accelerometer.

29. ___Mark medial tibial tri-axial accelerometer location at **1cm superior to impact location on medial side of the leg,** ensuring structural integrity of MCL is not jeopardized
30. ___Attach medial tibial tri-axial accelerometer
31. ___Ensure all accelerometer wires have some relief so as not to damage leads during testing
32. ___Attach photo-target pins to tibia.
33. ___ Strap foot down to table
34. ___Take all required positional and anthropometric measurements (Pre-Test Positioning Measurements sheet).
35. ___Remove and dispose of protective clothing, wash hands, and put on new protective equipment.
36. ___Check previous section and all measurement sheets for completion of all steps.
37. ___Make sure all faro arm measurements are saved

Test Performance Phase and Positioning:
(See Positioning & Instrumentation Measurements Protocol)

(Right leg)

1. _/_/_/_/_Ensure that universal precautions are being enforced.
2. _/_/_/_/_Make sign board.
3. _/_/_/_/_Configure Yokogawa data acquisition system (See Yokogawa Operating Instructions.)
4. _/_/_/_/_Set-up high speed camera and lighting and flash.
5. _/_/_/_/_Place padding on impactor face.
6. _/_/_/_/_Clean impactor ram and lubricate the shaft.
7. _/_/_/_/_Check connection of ram accelerometer, tibial and femoral accelerometers, and light traps.
8. _/_/_/_/_Check positioning to ensure free flight of the ram.
9. _/_/_/_/_Raise the impact table to align the tibial tubercle with top edge of impact interface.
10. _/_/_/_/_Record the distance from the cameras to the tibial photo target.
11. _/_/_/_/_Connect all instrumentation, verify continuity, balance, etc.
12. _/_/_/_/_Position event tape on foam and lower extremity; hook up event switches.
13. _/_/_/_/_Zero all recording channels.
14. _/_/_/_/_Zero light trap reading.
15. _/_/_/_/_Double check photographic targets.
16. _/_/_/_/_Place inch tape in field of view for photographic analysis.
17. _/_/_/_/_Place sign board.
18. _/_/_/_/_Still photography.
19. _/_/_/_/_Final camera focus.
20. _/_/_/_/_Ensure all test data sheets are complete (See Test Data Protocol.)
21. _/_/_/_/_Apply tension to quadriceps tendon (approximately 50 Lbs.)

22. _/_/_/_/_Double check impactor height-avoid impact of photo targets.
23. _/_/_/_/_**TURN FLASH ON.**
24. _/_/_/_/_Check previous page for completion of all steps.
25. _/_/_/_/_Conduct test, fire impactor.
26. _/_/_/_/_Check knee, data and video for injury before next test

Post-Test:

(**R/L)**

1. ___/__ Ensure that universal precautions are being enforced.
2. ___/__ Record velocity from light traps, pressure, date, time, etc.
3. ___/__ Still photography.
4. ___/__Remove padding from the impactor face.
5. ___/__ Download the data from the high-speed cameras.
6. ___/__ Remove lower extremity from the lift table and place on gurney.
7. ___/__ Remove all instrumentation, saving all instruments and noting any irregularities.
8. ___/__ Photograph, record and note any relevant observations.
9. ___/__ Prepare lower extremity for post-MRI and x-ray.

Post-MRI & X-Rays:

(See MRI/X-Ray Protocol)

(**R/L)**

1. ___/__ Transport lower extremity(s) in proper bag, sheets and gloves to imaging facility outside of Means Hall.
2. ___/__ Prepare MRI device for lower extremity(s) using knee coil and towels for bracing.
3. ___/__ MRI scan(s) on knee(s) per protocol from Petra Schmalbrock. Check for cruciate and collateral ligament continuity, meniscus quality and cartilage quality.
4. ___/__ Record saved file name and specify whether right or left leg for file retrieval.
5. ___/__ Disinfect the MRI machine.
6. ___/__ Transport lower extremity(s) in proper bag, sheets and gloves to X-Ray facility in Rhodes Hall.
7. ___/__ Prepare the x-ray machine.
8. ___/__ 1st x-ray anterior-posterior view.
9. ___/__ 2nd x-ray medial-lateral view.
10. ___/__ Record x-ray file names and session number for file retrieval (specify whether right or left.)
11. ___/__ Transport the lower extremity(s) to room 3024 Graves Hall and place in cooler.
12. ___/__ Prepare femur section for bone densiometry.
13. ___/__ Take femur to Davis Center for bone densiometry and record data for file retrieval.

14. ___/__ Check previous section for completion of all steps.

Autopsy/Dissection:

(See Autopsy Dissection Report)

(**R/L)**

1. ___/__ Determine / document trauma; specifically, that involving any PCL tears and/or avulsion fractures (Refer to.Doc).
2. ___/__ Photograph significant injury.

Laboratory Clean-up:

1. _____ Ensure that universal precautions are being enforced.
2. _____ Complete all steps on the workroom decontamination checklist.
3. _____ Place all contaminated disposables in bio-hazard container.
4. _____ Soak and/or scrub all non-sharp instruments with bleach solution.
5. _____ Scrub counter tops, table tops, impactor surface and gurney with bleach solution.
6. _____ Check instrumentation and cables for any blood contamination, and if found, remove with bleach solution.
7. _____ Sweep and mop floor with bleach solution.
8. _____ Complete all steps on the hand washing station inspection checklist.
9. _____ Check stock of protective clothing and, if necessary, restock for next test.
10. _____ Check previous section for completion of all steps.
11. _____ Sign and date the workroom decontamination checklist.
12. _____ Return all specimen remains to Mark Whitmer in OSU morgue.
13. _____ Prepare Biohazard box for collection and call Environmental Health and Safety for Biohazard Pickup (Tuesdays and Thursdays.)

Miscellaneous Test Notes:

DECONTAMINATION CHECKLIST
Room 3024 Graves Hall

Initials **Task**

_____ _____ gallons of disinfectant solution (2 oz. Chlorine bleach and 1 gallon fresh water) were prepared at Time:_____ on Date:_____ (**MUST BE PREPARED FRESH FOR EACH TEST!**)
by:_____.

_____All areas with gross contamination by blood or other potentially infectious materials were wiped clean using appropriately absorbent materials.

_____The operating table, gurney and all countertops, bench-tops and other surfaces which may have been contaminated by blood or other potentially infectious materials were flooded with disinfectant solution and wiped dry with clean, absorbent, disposable towels.

_____All contaminated goggles, hand tools, re-useable sharps, measuring instruments and mounting blocks were cleaned of gross contamination over the sink, submersed in disinfectant solution and wiped dry with clean, absorbent, disposable towels.

_____Those items that cannot be submersed (e.g. Electronic instruments and hand tools) were thoroughly wiped with a clean, disposable towel soaked in disinfectant solution and wiped dry with clean, absorbent, disposable towels.

_____The impactor face was thoroughly wiped with a clean, disposable towel soaked in disinfectant solution and wiped dry with clean, absorbent disposable towels.

_____All disposable towels, cover-alls, shoe covers, gloves, etc. were collected in the appropriately labeled containers.

_____The floor of the room was mopped with disinfectant solution.

_____The mop was rinsed in fresh disinfectant solution.

_____The floor of the room was mopped with a regular detergent solution.

_____The red liner bags containing contaminated disposables were closed and placed in the holding area.

_____The inside and outer surfaces of the contaminated disposables container were thoroughly wiped with a clean, disposable towel soaked in disinfectant solution and wiped dry with clean, absorbent, disposable towels. And clean red liner bags were installed.

_____The sink was cleared of visible contamination, thoroughly wiped with a clean, disposable towel soaked in disinfectant solution and flushed with fresh water.

_____ _____

Signature Date

HANDWASHING STATION INSPECTION CHECKLIST

Sufficient quantities of non-abrasive soap, waterless cleaning solution or clean, solution impregnated towels are present.

Sufficient quantities of dry, absorbent paper towels are present.

The eyewash kit is present and in good working condition.

A properly labeled container for discarded towels is located nearby.

_____ _____

Signature Date

C. Sample Instrumentation Configuration

Tibia Research Test No. 0503HTI29L01 / 0503HTI47L02											
Channel Number	Serial No.	Channel Name	Phonetic Name of the Channel	Filter (CFC)	Polarity	Sensitivity	Range Unit	Range	Units	Excite Volt	Box - Slot, Channel
1	N.A.	EVENT	Event Channel	1000	+	1.000000	V	10	VOLTS	10	A1,1
2	74632	RAMXD	Ram Linear Potentiometer	1000	+	0.159467	V	5	CM	10	A1,2
3	687963	RAMPSI	Ram Fire Pressure	1000	+	0.005000	V	5	PSI	0	A1,3
4	J14908	RAMXG	Ram Accelerometer	1000	+	0.000255	mV	100	G	10	A1,4
5	0082FX	RAMFZ	Ram Force	1000	+	0.000393	mV/V	10	N	10	A2,1
6	0082FY	RAMFY	Ram Force	1000	+	0.000394	mV/V	10	N	10	A2,2
7	0082FZ	RAMFX	Ram Force	1000	+	0.000180	mV/V	10	N	10	A2,3
8	0082MX	RAMMZ	Ram Moment	1000	+	0.009839	mV/V	2.5	Nm	10	A2,4
9	0082MY	RAMMY	Ram Moment	1000	+	0.009700	mV/V	2.5	Nm	10	A3,1
10	0082MZ	RAMMX	Ram Moment	1000	+	0.015850	mV/V	2.5	Nm	10	A3,2
11	72059	HEELXF	Heel Force	1000	+	0.000231	mV/V	0.5	N	10	A3,3
12	73373	HEELZF	Heel Force	1000	+	0.000186	mV/V	0.5	N	10	A3,4
13	1121-0005 Y	KNEEDVRTL	PCL Displacement P-L	1000	+	0.923000	V	10	Mm	0	A4,1
14	1121-0010 B	KNEEDVRTM	PCL Displacement A-M	1000	+	0.686000	V	10	Mm	0	A4,2
15	32725	QTENFZ	Quadriceps Tendon Force	1000	+	0.000700	mV/V	1	N	10	A4,3
16	76FX	FEMFX	Femur Force	1000	+	0.000138	mV/V	2.5	N	10	A4,4
17	76FY	FEMFY	Femur Force	1000	+	0.000138	mV/V	2.5	N	10	A5,1
18	76FZ	FEMFZ	Femur Force	1000	+	0.000055	mV/V	2.5	N	10	A5,2
19	76MX	FEMMX	Femur Moment	1000	+	0.004962	mV/V	1	Nm	10	A5,3
20	76MY	FEMMY	Femur Moment	1000	+	0.004864	mV/V	1	Nm	10	A5,4
21	76MZ	FEMMZ	Femur Moment	1000	+	0.009563	mV/V	1	Nm	10	A6,1
22	P17743	FEMXG	Anterior Femur Accel	1000	+	0.000147	mV	100	G	10	A6,2
23	J17705	FEMYG	Anterior Femur Accel	1000	-	0.000234	mV	100	G	10	A6,3
24	AMR49	FEMZG	Anterior Femur Accel	1000	+	0.000201	mV	100	G	10	A6,4
25	01G18-F07	MEDTIBZG	Medial Side Tibia Accel	1000	-	0.000227	mV	100	G	10	A7,1
26	02A18-N07	MIDTIBYG	Medial Side Tibia Accel	1000	+	0.000199	mV	100	G	10	A7,2
27	AL40	MEDTIBXG	Medial Side Tibia Accel	1000	+	0.000253	mV	100	G	10	A7,3
28	03F03F09-N14	ANTIBXG	Anterior Side Tibia Accel	1000	+	0.000193	mV	100	G	10	A7,4
29	99102-F06	ANTIBZG	Anterior Side Tibia Accel	1000	+	0.000187	mV	100	G	10	A8,1
30	02I02I10-N12	ANTIBYG	Anterior Side Tibia Accel	1000	-	0.000204	mV	100	G	10	A8,2

D.

Logfile Processing.log

Infile 0602HTI29L04.dx3; Outfile 0602HTI29L04TP.dx3, 100 overWrite

Read(1) EVENT; Writ(1)

Read(1) RAMXD; Zero(1) -.24 -.120; Bwf(1) 300; Writ(1)

Read(1) RAMXD, Output; DIFF(1) 1; Div(1) 100; Units(1) m/sec; WRIT(1)

RAMXD_VEL

Read(1) RAMXG; Zero(1) -.24 -.120; Bwf(1) 300; Writ(1)

Read(1) RAMXG, Output; Mult(1) -1; Mult(1) 9.80665; Integ(1) 0 1; Units(1) M/S;

Writ(1) RAMXG_VEL

Read(1) RAMXG, Output; Mult(1) -1; Mult(1) 9.80665; Mult(1) 22.75; Units(1) N;

Writ(1) RAMXG_FORCE

Read(1) RAMFX; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) RAMFY; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) RAMFZ; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) RAMMX; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) RAMMY; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) RAMMZ; Zero(1) -.24 -.120; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) FEMFX; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMYF

Read(1) FEMFY; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMXF

Read(1) FEMFZ; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMZF

Read(1) FEMMX; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMYM

Read(1) FEMMY; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMXM

Read(1) FEMMZ; Zero(1) -.249 -.120; Bwf(1) 600; Writ(1) FEMZM

Read(1) FEMFX; Bwf(1) 600; Writ(1) FEMFY_NotZeroed

Read(1) FEMFY; Bwf(1) 600; Writ(1) FEMFX_NotZeroed

Read(1) FEMFZ; Bwf(1) 600; Writ(1) FEMFZ_NotZeroed

Read(1) FEMMX; Bwf(1) 600; Writ(1) FEMMY_NotZeroed

Read(1) FEMMY; Bwf(1) 600; Writ(1) FEMMX_NotZeroed

Read(1) FEMMZ; Bwf(1) 600; Writ(1) FEMMZ_NotZeroed

Read(1) HEELFX; Zero(1) -.249 -.010; Mult(1) -1; Bwf(1) 600; Writ(1)

Read(1) HEELFZ; Zero(1) -.249 -.010; Bwf(1) 600; Writ(1)

Read(1) HEELFX; Mult(1) -1; Bwf(1) 600; Writ(1) HEELXF_NotZeroed

Read(1) HEELFZ; Bwf(1) 600; Writ(1) HEELzF_NotZeroed

!Read(1) KNEEDVRTL; Mult(1) -1; Zero(1) -.249 -.010; Bwf(1) 300; Writ(1)

Read(1) KNEEDVRT; Mult(1) -1; Zero(1) -.249 -.010; Bwf(1) 300; Writ(1)

!DVRT x (Total Ligament Length/Barb Length) = PCL?_DISP.

!Mult(1) ? = Total Ligament Length/Barb Length

!KNEELDVRTL Total Ligament Length (mm) =

!KNEELDVRTL Barb Length (mm) =

!KNEELDVRTM Total Ligament Length (mm) = 40

!KNEELDVRTM Barb Length (mm) = 19

!Read(1) KNEEDVRTL, Output; Mult(1) 2; Writ(1) PCLL_STRETCH

Read(1) KNEEDVRT, Output; Mult(1) 2.106; Writ(1) PCLM_STRETCH

Read(1) KNEEDVRT, Output; DIFF(1) 1; Units(1) mm/sec; WRIT(1)
KNEEDVRT_VEL

!Read(1) KNEEDVRT, Output; DIFF(1) 1; Units(1) mm/sec; WRIT(1)
KNEEDVRTM_VEL

Read(1) QTENFZ; Zero(1) -.249 -.010; Bwf(1) 600; Writ(1) QTENZF_C600

Read(1) QTENFZ; Bwf(1) 600; Writ(1) QTENZF_NotZeroed

Read(1) FEMG3; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) FEMG3

Read(1) FEMG2; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) FEMG2

Read(1) FEMG1; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) FEMG1

Read(1) FEMG1, Output; Mult(1) 9.80665; Integ(1) 0 1; Units(1) M/S; Writ(1)
FEMG1_Vel

Read(1) FEMG1, Output; Mult(1) 9.80665; Integ(1) 0 1; Integ(1) 0 1; Mult(1) 1000;
Units(1) mm; Writ(1) FEMG1_Disp

Read(1) MEDTIBG2; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) MEDTIBG2

Read(1) MEDTIBG2, Output; Mult(1) 9.80665; Integ(1) 0 1; Units(1) M/S; Writ(1) MEDTIBG2_Vel

Read(1) MEDTIBG2, Output; Mult(1) 9.80665; Integ(1) 0 1; Integ(1) 0 1; Mult(1) 1000; Units(1) mm; Writ(1) MEDTIBG2_Disp

Read(1) MEDTIBG3; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) MEDTIBG3

Read(1) MEDTIBG1; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) MEDTIBG1

Read(1) ANTTIBG3; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) ANTTIBG3

Read(1) ANTTIBG3, Output; Mult(1) 9.80665; Integ(1) 0 1; Units(1) M/S; Writ(1) ANTTIBG3_Vel

Read(1) ANTTIBG3, Output; Mult(1) 9.80665; Integ(1) 0 1; Integ(1) 0 1; Mult(1) 1000; Units(1) mm; Writ(1) ANTTIBG3_Disp

Read(1) ANTTIBG1; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) ANTIBG1

Read(1) ANTTIBG2; Zero(1) -.249 -.010; Bwf(1) 1000; Writ(1) ANTIBG2

Read(1) FEMG1_Disp, Output; Read(2) ANTTIBG3_Disp, Output; Subc 1 2; Writ(1) RelTibDisp

Read(1) MEDTIBG2_Disp, Output; Read(2) ANTTIBG3_Disp, Output; Subc 1 2; Writ(1) RelAntVsMed

!

!

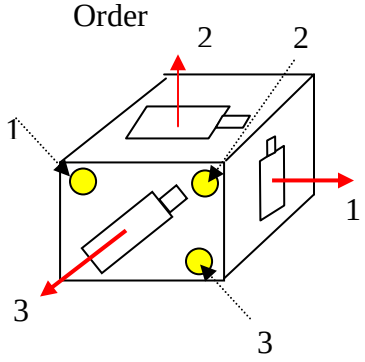
Exit, Close

E. Faro Arm Checklist

Faro Arm measurements		
File name of Faro arm measurements		
Units of Faro arm measurement		
	Right	**Left**
	(Point number)	**(Point number)**
Pre-Test Anthropometric Measurements		
(taken after leg is in position and potted)		
Most Inferior posterior point of calcaneus		
Insertion of patellar tendon on tibial tuberosity		
Most superior point of the knee		
Proximal medial margin of tibia		
Proximal medial margin of malleolus		
distal great toe		
most medial metatarsal-phalangeal joint		
most proximal metatarsal-phalangeal joint		
superior head of fibula		
medial tibial condyle		
medial femoral condyle		
lateral femoral condyle		
anterior tibia approximately 2 Inches inferior to impact location		
anterior tibia approximately 4 Inches inferior to impact location		
anterior tibia approximately 6 Inches inferior to impact location		
Pre Test Positioning Measurements	**Right**	**Left**
Impact location		
Heel Load plate (X) All four corners (behind foot)		
1. inferior-medial		
2. inferior-lateral		

3. superior-lateral		
4. superior-medial		
Heel Load plate (Z) All four corners (under foot)		
1. anterior-medial		
2 anterior-lateral		
3. posterior-lateral		
4. posterior-medial		
Femoral tri-axial accel **(In a clockwise fashion looking at the block dimples** **See figure below)**		
1. Dimple 1 (Accel 1 – FEMG1 /)		
2. Dimple 2 (Accel 2 – FEMG2 /)		
3. Dimple 3 (Accel 3 – FEMG3 /)		

Point Digitization Order



Front Tibial tri-axial accel (In a clockwise fashion looking at the block dimples)		
See figure above		
1. Dimple 1 (Accel 1 – ANTIBG1 /)		
2. Dimple 2 (Accel 2 – ANTIBG2 /)		
3. Dimple 3 (Accel 3 – ANTIBG3 /)		
Medial Tibial tri-axial accel (In a clockwise fashion looking at the block dimples) **See figure above**		
1. Dimple 1 (Accel 1 – MEDTIBG1 /)		
2. Dimple 2 (Accel 2 – MEDTIBG2 /)		
3. Dimple 3 (Accel 3 – MEDTIBG3 /)		

*** accelerometer reads (-) according to J211, R denotes right leg only**		
Femoral Load Cell(all four corners)		
1. Superior		
2. Lateral		
3. Inferior		
4.Medial		
Line Down Femur (starting at knee and moving toward hip)		
Point 1		
Point 2		
Point 1 on femur cup		
Point 2 on femur cup		

F. Accelerometer Transformation MATLAB Code

```
%----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006, ADAPTED BY KIEL PFEFFERLE
4/26/2006
% ----------------------------------------
% THIS PROGRAM IS THE CONTROL MODULE THAT EXECUTES THE FUNCTIONS
% THE FILES LISTED IN 'A' BELOW ARE THE TEXT FILES THAT LIST THE XYZ
% COORDINATES OF THE POINTS DIGITIZED
% 'B' POINTS TO THE FILES THAT CONTAIN THE FILTERED DATA IN ASCII
FORMAT
% 'C' IS OUTPUT FILES THAT CONTAIN THE TRANSFORMED DATA FOR EACH BLOCK
% 'D' IS OUTPUT FILES THAT CONTAIN THE XYZ POSITION OF EACH BLOCK
RELATIVE
% TO THE UPPER SPINE POINT IN THE BODY COORDINATE SYSTEM


% TESTNAME is the filename of the test that is being processed
clear variables
A=['0602HTILpointdata.txt'];    % input - digitized point data for all
blocks
B=['0602HTI29L04PreAccelTrans.txt'];     % input - filtered/zeroed
accelerometer data
C=['0602HTI29L04trans.txt'];    % output - transformed accelerometer
data wrt BCS
D=['0602HTI29L04pos.txt'];      % output - initial position data for
all blocks wrt IMPACT LOCATION
E=['0602HTI29L04disp.txt'];     % output - integrated transformed
accelerometer data wrt IMPACT LOCATION
% F=['TESTNAMEBCS.txt'];    % text file that contains the video
displacement data
TEST=1
for i=TEST:TEST
    POINTLIST=load('-ascii',A(i,:));
    TESTDATA=load('-ascii',B(i,:));
    PROCOUT=C(i,:);
    POSOUT=D(i,:);
    DISPOUT=E(i,:);
    TIBposition(POINTLIST,POSOUT)
    POSITIONOUT=load('-ascii',D(i,:));
    TIBprocess(POINTLIST,TESTDATA,PROCOUT,DISPOUT,POSITIONOUT)
end
'done'

% PATH = 1 plots the path of the individual accelerometers
% PATH = 0 plots the circle that connects the accelerometers
%PATH=1;
%ACCEL=load('-ascii',E(TEST,:));
% VIDEO=load('-ascii',F(TEST,:));
%graphic(ACCEL,PATH)    % VIDEO variable removed for actual tests
%----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006,ADAPTED BY KIEL PFEFFERLE
4/26/2006
% ----------------------------------------
% THIS SCRIPT READS THE BCS, THE FILTERED ACCERLATION DATA AND THE ijk
```

```
% VECTORS FOR EACH BLOCK, PERFORMS THE TRANSFORMATION AND THEN OUTPUTS
THE
% RESULTS TO THE XYZ TIME HISTORIES

%  VERY IMPORTANT TO CHECK PHOTOS TO MAKE SURE AXIS ARE CORRECT
function[R] = ANTTIBtransform(array,BCS,one,two,three)
% determine orientation matrix for block then rotation matrix
a=array(2,:)-array(1,:);
k=a/norm(a);
b=array(3,:)-array(2,:);
j=b/norm(b);
i=cross(j,k);
j=cross(k,i);
% set Body Coordinate System to x,y,z axes
xaxis=BCS(1,:);
yaxis=BCS(2,:);
zaxis=BCS(3,:);
% find transformation matrix
matrix=zeros(3,3);
matrix(1,1)=dot(i,xaxis);
matrix(1,2)=dot(j,xaxis);
matrix(1,3)=dot(k,xaxis);
matrix(2,1)=dot(i,yaxis);
matrix(2,2)=dot(j,yaxis);
matrix(2,3)=dot(k,yaxis);
matrix(3,1)=dot(i,zaxis);
matrix(3,2)=dot(j,zaxis);
matrix(3,3)=dot(k,zaxis);
% multiply rotation matrix by accel data
accel=[three one two]';
R=matrix*accel;
% matrixcheck=matrix*matrix'

end


%-----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006,ADAPTED BY KIEL PFEFFERLE
4/26/2006
% -----------------------------------------
% THIS SCRIPT READS THE BCS, THE FILTERED ACCERLATION DATA AND THE ijk
% VECTORS FOR EACH BLOCK, PERFORMS THE TRANSFORMATION AND THEN OUTPUTS
THE
% RESULTS TO THE XYZ TIME HISTORIES

%  VERY IMPORTANT TO CHECK PHOTOS TO MAKE SURE AXIS ARE CORRECT
function[R] = FEMtransform(array,BCS,one,two,three)
% determine orientation matrix for block then rotation matrix
a=array(2,:)-array(1,:);
i=a/norm(a);
b=array(3,:)-array(2,:);
j=b/norm(b);
k=cross(i,j);
j=cross(k,i);
% set Body Coordinate System to x,y,z axes
xaxis=BCS(1,:);
```

```
yaxis=BCS(2,:);
zaxis=BCS(3,:);
% find transformation matrix
matrix=zeros(3,3);
matrix(1,1)=dot(i,xaxis);
matrix(1,2)=dot(j,xaxis);
matrix(1,3)=dot(k,xaxis);
matrix(2,1)=dot(i,yaxis);
matrix(2,2)=dot(j,yaxis);
matrix(2,3)=dot(k,yaxis);
matrix(3,1)=dot(i,zaxis);
matrix(3,2)=dot(j,zaxis);
matrix(3,3)=dot(k,zaxis);
% multiply rotation matrix by accel data
accel=[one two three]';
R=matrix*accel;
% matrixcheck=matrix*matrix'

end


%-----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006,ADAPTED BY KIEL PFEFFERLE
4/26/2006
% -----------------------------------------
%
function[D] = integrate(array)
ONE=array(1,:);
TWO=array(2,:);
THREE=array(3,:);
DISPONE=(.00005*cumtrapz(.00005*cumtrapz(ONE*9.8066)))*1000;
DISPTWO=(.00005*cumtrapz(.00005*cumtrapz(TWO*9.8066)))*1000;
DISPTHREE=(.00005*cumtrapz(.00005*cumtrapz(THREE*9.8066)))*1000;
D=[DISPONE; DISPTWO; DISPTHREE];

end


%-----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006, ADAPTED BY KIEL PFEFFERLE
4/26/2006
% -----------------------------------------
% THIS SCRIPT READS THE BCS, THE FILTERED ACCERLATION DATA AND THE ijk
% VECTORS FOR EACH BLOCK, PERFORMS THE TRANSFORMATION AND THEN OUTPUTS
THE
% RESULTS TO THE XYZ TIME HISTORIES

%  VERY IMPORTANT TO CHECK PHOTOS TO MAKE SURE AXIS ARE CORRECT
function[R] = MEDTIBtransform(array,BCS,one,two,three)
% determine orientation matrix for block then rotation matrix
a=array(2,:)-array(1,:);
k=a/norm(a);
b=array(2,:)-array(3,:);
i=b/norm(b);
j=cross(k,i);
```

```
k=cross(i,j);

% set Body Coordinate System to x,y,z axes
xaxis=BCS(1,:);
yaxis=BCS(2,:);
zaxis=BCS(3,:);
% find transformation matrix
matrix=zeros(3,3);
matrix(1,1)=dot(i,xaxis);
matrix(1,2)=dot(j,xaxis);
matrix(1,3)=dot(k,xaxis);
matrix(2,1)=dot(i,yaxis);
matrix(2,2)=dot(j,yaxis);
matrix(2,3)=dot(k,yaxis);
matrix(3,1)=dot(i,zaxis);
matrix(3,2)=dot(j,zaxis);
matrix(3,3)=dot(k,zaxis);
% multiply rotation matrix by accel data
accel=[two three one ]';
R=matrix*accel;
% matrixcheck=matrix*matrix'

end


%-----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006, ADAPTED BY KIEL PFEFFERLE
4/26/2006
% ----------------------------------------
% THIS SCRIPT TAKES THE DIGITIZED POINT DATA AND FINDS THE XYZ
COORDINATES
% OF EACH BLOCK (POINT '2') IN THE BCS AND OUTPUTS TO THE FILES LISTED
IN
% THE CONTROL PROGRAM

function[M]=TIBposition(POINTLIST,POSOUT)

IMPACTLOC=POINTLIST(3,2:4);
FEM=POINTLIST(13,2:4);
TIB=POINTLIST(2,2:4);
% create a line between the IMPACTLOCATION AND TIBIA points
% then a line between the IMPACT LOCATION AND FEMUR
% cross these two lines to find the vector for the y axis
% then cross the spine line and the Ytemp to get the x axis vector
% finally find the unit vectors for all three axes
Ztemp=TIB-IMPACTLOC;
SpStLine=IMPACTLOC-FEM;
Ytemp=cross(Ztemp,SpStLine);
Xtemp=cross(Ytemp,Ztemp);
xaxis=Xtemp/norm(Xtemp);
yaxis=Ytemp/norm(Ytemp);
zaxis=Ztemp/norm(Ztemp);
```

```
% read in the number '2' x,y,z coordinates and then find relative
distance
% to upper spine point in lab coordinate system
% then find the projections of the vector representing the No.2 point
on
% the body coordinate system axes
% last combine into a single triplet
FEMG=POINTLIST(4,2:4);
FEMG=FEMG-IMPACTLOC;
FEMGx=((dot(FEMG,xaxis))/(dot(xaxis,xaxis)));
FEMGy=((dot(FEMG,yaxis))/(dot(yaxis,yaxis)));
FEMGz=((dot(FEMG,zaxis))/(dot(zaxis,zaxis)));
FEMG=[FEMGx FEMGy FEMGz];

ANTTIB=POINTLIST(7,2:4);
ANTTIB=ANTTIB-IMPACTLOC;
ANTTIBx=((dot(ANTTIB,xaxis))/(dot(xaxis,xaxis)));
ANTTIBy=((dot(ANTTIB,yaxis))/(dot(yaxis,yaxis)));
ANTTIBz=((dot(ANTTIB,zaxis))/(dot(zaxis,zaxis)));
ANTTIB=[ANTTIBx ANTTIBy ANTTIBz];

MEDTIB=POINTLIST(10,2:4);
MEDTIB=MEDTIB-IMPACTLOC;
MEDTIBx=((dot(MEDTIB,xaxis))/(dot(xaxis,xaxis)));
MEDTIBy=((dot(MEDTIB,yaxis))/(dot(yaxis,yaxis)));
MEDTIBz=((dot(MEDTIB,zaxis))/(dot(zaxis,zaxis)));
MEDTIB=[MEDTIBx MEDTIBy MEDTIBz];

%-------------------------------------------------------------------
%Output all of the variables
proc=[FEMG; ANTTIB; MEDTIB];
save(POSOUT,'proc','-ascii')

%-----------------------------------------
% WRITTEN BY JOSHUA M. SHAW 2/25/2006,ADAPTED BY KIEL PFEFFERLE
4/26/2006
% -----------------------------------------
% THIS FUNCTION PROGRAM COMPENSATES THE RAM FORCE FOR INERTIAL EFFECTS
% IT ALSO READS IN THE XYZ POINTS AND CREATES THE BODY COORDINATE
SYSTEM
% (BCS) AND THEN READS IN THE FILTERED DATA AND SENDS THE INPUTS TO THE
% TRANSFORM FUNCTION
% THE OUTPUT IS SAVED TO THE FILE NAMES LISTED IN THE CONTROL PROGRAM

function[J]=TIBprocess(POINTLIST,TESTDATA,PROCOUT,DISPOUT,POSITIONOUT)
Time=TESTDATA(:,1);
n=length(Time)-2;
Time=TESTDATA(3:n,1);
%RAMG=TESTDATA(3:n,5);
%RAMF=TESTDATA(3:n,6);
%RAMFc=-(RAMF-(RAMG*9.8066*8.02));


IMPACTLOC=POINTLIST(3,2:4);
FEM=POINTLIST(13,2:4);
```

```
TIB=POINTLIST(2,2:4);
% create a line between the IMPACTLOCATION AND TIBIA points
% then a line between the IMPACT LOCATION AND FEMUR
% cross these two lines to find the vector for the y axis
% then cross the spine line and the Ytemp to get the x axis vector
% finally find the unit vectors for all three axes
Ztemp=TIB-IMPACTLOC;
SpStLine=IMPACTLOC-FEM;
Ytemp=cross(Ztemp,SpStLine);
Xtemp=cross(Ytemp,Ztemp);
xaxis=Xtemp/norm(Xtemp);
yaxis=Ytemp/norm(Ytemp);
zaxis=Ztemp/norm(Ztemp);
BCS=[xaxis;yaxis;zaxis];

% read the points for the block and the accel data then feed to
'transform'
% function which returns the transformed data
FEMG=POINTLIST(4:6,2:4);
FEMG1=TESTDATA(3:n,4);
FEMG2=TESTDATA(3:n,3);
FEMG3=TESTDATA(3:n,2);
xyz=FEMtransform(FEMG,BCS,FEMG1,FEMG2,FEMG3);
FEMGx=xyz(1,:)';
FEMGy=xyz(2,:)';
FEMGz=xyz(3,:)';
% UPSPdiff=((sqrt(UPSP1.^2+UPSP2.^2+UPSP3.^2))-
(sqrt(UPSPx.^2+UPSPy.^2+UPSPz.^2)))
FEMGi=POSITIONOUT(1,:);
displace=integrate(xyz);
FEMGDx=displace(1,:)';%+FEMGi(1);
FEMGDy=displace(2,:)';%+FEMGi(2);
FEMGDz=displace(3,:)';%+FEMGi(3);
% plot(Time,UPSPDx,'g',Time,UPSPDy,'b',Time,UPSPDz,'r')


ANTTIB=POINTLIST(7:9,2:4);
ANTTIB1=TESTDATA(3:n,9);
ANTTIB2=TESTDATA(3:n,10);
ANTTIB3=TESTDATA(3:n,8);
xyz=ANTTIBtransform(ANTTIB,BCS,ANTTIB1,ANTTIB2,ANTTIB3);
ANTTIBx=xyz(1,:)';
ANTTIBy=xyz(2,:)';
ANTTIBz=xyz(3,:)';
% LOSPdiff=((sqrt(LOSP1.^2+LOSP2.^2+LOSP3.^2))-
(sqrt(LOSPx.^2+LOSPy.^2+LOSPz.^2)))
ANTTIBi=POSITIONOUT(2,:);
displace=integrate(xyz);
ANTTIBDx=displace(1,:)';%+ANTTIBi(1);
ANTTIBDy=displace(2,:)';%+ANTTIBi(2);
ANTTIBDz=displace(3,:)';%+ANTTIBi(3);


MEDTIB=POINTLIST(10:12,2:4);
MEDTIB1=TESTDATA(3:n,7);
MEDTIB2=TESTDATA(3:n,5);
```

```
MEDTIB3=TESTDATA(3:n,6);
xyz=MEDTIBtransform(MEDTIB,BCS,MEDTIB1,MEDTIB2,MEDTIB3);
MEDTIBx=xyz(1,:)';
MEDTIBy=xyz(2,:)';
MEDTIBz=xyz(3,:)';
% LPOBdiff=((sqrt(LPOB1.^2+LPOB2.^2+LPOB3.^2))-
(sqrt(LPOBx.^2+LPOBy.^2+LPOBz.^2)));
MEDTIBi=POSITIONOUT(3,:);
displace=integrate(xyz);
MEDTIBDx=displace(1,:)';%+MEDTIBi(1);
MEDTIBDy=displace(2,:)';%+MEDTIBi(2);
MEDTIBDz=displace(3,:)';%+MEDTIBi(3);




%-------------------------------------------------------------------
%Output all of the variables
proc=[Time FEMGx FEMGy FEMGz ANTTIBx ANTTIBy ANTTIBz MEDTIBx MEDTIBy
MEDTIBz];
%  S g g g g g g g g g
% list=['N '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g
'; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g '; 'g
'; 'g '; 'g '; 'g '; 'g '; 'g ']'
save(PROCOUT,'proc','-ascii')


%-------------------------------------------------------------------
%Output all of the variables
proc=[Time FEMGDx FEMGDy FEMGDz ANTTIBDx ANTTIBDy ANTTIBDz MEDTIBDx
MEDTIBDy MEDTIBDz];
%utput units s mm mm mm mm mm mm mm mm mm
save(DISPOUT,'proc','-ascii')
```